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Comparison of Various INDOT Testing Methods and Procedures to Quantify Variability in Measured Bituminous and Concrete Properties

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INDOT Research

TECHNICAL *Summary*

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Comparison of Various INDOT Testing Methods and Procedures to Quantify Variability in Measured Bituminous and Concrete Properties

Introduction

The objective of this study was to assess the variability that is associated with INDOT QC/QA testing procedures. Variability can be attributed to the "testing variability" that includes inherent material, sampling, and testing variability, and "production variability" that includes the variability associated with production. Each of these sources of variability is combined to produce the total variation, which is measured by various testing protocols.

This study was performed by analyzing the existing test data that had been collected by INDOT and INDOT contractors, on paving and superstructure contracts in Indiana, as well as conducting a laboratory study that was performed at Purdue University. The objective of the laboratory study was to assess the test methods that turned out to be problematic based on the findings from the analysis of existing data, or study test methods for which previous test data was not available.

Findings

Results for HMA:

Overall it can be concluded that the hypothesis of increased testing variation associated with the calculated quantities, presented in the problem statement, tuned out to be false. Based on literature, research has indicated that the allowed variability in the materials testing can lead to unacceptable variation of the calculated quantities computed from the acceptable test results. Based on Monte Carlo simulation, the allowed variation in the tested bulk and theoretical maximum specific gravity values for asphalt concrete mixtures could produce unacceptable air void content variation. The simulation runs used ASTM precision statements.

There are two reasons why this hypothesis turned out to be false. Firstly, an important change during the course of this research has taken place, namely, a change in the ASTM precision statements. A new 2004 version of the ASTM D2726 method which measures the bulk specific gravity of compacted mixture has a considerably tighter precision statement compared to the older version of the method. The new ASTM precision statement is now in agreement with the AASHTO precision statement.

The second thing is that the actual measured testing variation measured from the volumetric database was smaller than was estimated based on the Monte Carlo simulation using the "old" ASTM precision statements. Research showed that the measured and theoretical or allowed AASHTO (1s) limits agreed very well.

An important part of the study was to assess the precision statements for the calculated volumetric quantities, SGC pill air voids content, in-place density and pill VMA. The ASTM D4460 standard: "*Calculating Precision Limits Where Values are calculated from Other Test Methods*" gives equations to obtain the precision limit for the air voids content, but (1s) limit for the VMA has not existed. Based on the ASTM D4460 equations were developed for obtaining the (1s) limit for the VMA.

From the analysis of the INDOT volumetric acceptance and quality control data measured by

INDOT and contractors between 2001 and 2002 the following observations were made:

- The testing variation for the gyratory pill and core bulk specific gravity G_{mb} tests was within (0.0022 to 0.0066) of the allowable AASHTO T275 (1s) limit (0.007).
- The testing variation for the maximum theoretical specific gravity G_{mm} tests was above (0.0079) the allowable AASHTO T209 (1s) limit (0.004). This was further investigated in laboratory study conducted by Purdue.
- Testing variation was not increased by increase in the aggregate nominal size.
- The estimated testing variation for the gyratory pill air voids content (0.27 - 0.31) was within the AASHTO (1s) limit (0.32). The total variation ranged from 0.73 to 0.93 suggesting that 60% of the total variation was associated with the production variation.
- The estimated testing variation for the gyratory pill VMA was slightly above (0.24-0.31) the AASHTO (1s) limit (0.25). The total variation ranged from 0.56 to 0.62 suggesting that up to 50% of the total variation was associated with production variation.
- The estimated testing variation for the core air voids content and density was within or slightly above 0.35 to 0.42 the AASHTO (1s) limit (0.32). The total variation ranged from 1.41 to 1.52 suggesting that 70% of the total variation was associated with the production variation.
- Testing variation could not be assessed for binder content because lack of replicate tests. The total variation ranged from 0.23 to 0.26. If AASHTO (1s) limit (0.004) is used for testing variation then approximately 85% of the total variation was associated with the production variation.

Based on the measured total variation a statistical probability of test data being outside the tolerance limits (being in the penalty range) were estimated to be as follows:

- The overall mean for SGC pill air voids content was 3.6% while the target is 4%. With one-sigma total variation of (0.93) there is 95% probability that 33% of the test data is outside the air voids content tolerance limits of 4 ±1%.
- The overall mean for SGC pill VMA was 14.06% while the average target from each JMF was 14.48%. With one-sigma total variation of (0.62) there is 95% probability that 17% of the test data is outside the VMA tolerance limits of 14.48 ±1%.
- The overall mean for binder content was 5.31% while target was not specified in the database. With one-sigma total variation of (0.26) there is 95% probability that 5% of the test data is outside the binder content tolerance limits of ±0.5% if the measured P_b is exactly the target P_b.
- The overall mean for core density (T166) was 92.4% while the full pay target is 92.5%. With one-sigma total variation of (0.35) there is 95% probability that 39% of the test data is in the penalty range having less than 92% density.
- The overall mean for core density (T275) was 90.9% while the full pay target is 92.5%. With one-sigma total variation of (0.42) there is 95% probability that 73% of the test data is in the penalty range having less than 92% density.

Results for PCC:

From the analysis of the PCC data collected and the following observations were made:

- The testing variability for the plastic air content test was within the allowable limits (0.28) with values that ranged from 0.12 to 0.21. The total variability in concrete pavements ranged from 0.37 to 1.29 thereby suggesting that the majority of the variability was associated with production.
- The testing variability for the plastic unit weight was within the allowable limits (0.82) with values that ranged from 0.35 to 0.52. The total variability ranged from 0.86 to 2.20 thereby suggesting that the majority of the variability was associated with production.
- The testing variability for the flexural strength was generally within the allowable coefficient of variation limits (5.7% and 7.0%) with values that ranged from 2.4 to 6.5%. The total variability included production variation increased the measured variability to 13.3%.

- The compressive strength data indicated a variability that was at the AASHTO (1s) limit. Data from both a laboratory study and production samples exhibited about the same testing variability that was at the AASHTO (1s) limit (COV of 2.37%). While the compressive strength data from data source V had a COV of 3.7% was higher than the AASHTO allowable limits, this analysis however was performed using a relatively limited series of data that are based on a single laboratory study.
- The variability of the splitting tensile strength test was below the AASHTO (1s) limit of COV 5.0%.
- INDOT thickness testing in data source X yielded the testing variability limit 0.047 for single operator variation.
- The study on the variability of the specific gravity of aggregates was conducted to assess variation in aggregate properties from aggregates from the same source over time. The results of this analysis yielded the expected variability of those tests over time and was dependent on the source. This may be expected based on variations in mining operations.

RECOMMENDATIONS

<u>HMA Production</u>

Based on the study findings, it is recommended that INDOT uses (1s) of 0.32 for the SGC pill air voids content and in-place density precision, and (1s) of 0.25 for the pill VMA precision. The recommended VMA limit of 0.25 is quite tight; however, a tight limit can be justified due to the fact that the variation in the VMA values is highly detrimental for the in service pavement performance.

It is also recommended that INDOT establishes a quality control procedure to verify the correctness of the maximum specific gravity G_{mm} testing during production. This can be accomplished by randomly running replicate test. Also periodical testing of aggregate bulk specific gravity G_{sb} during mix production may help reduce the observed bias between mix design and field VMA values.

Based on limited laboratory testing it is recommended that Corelok method is not used to replace the AASHTO T85 testing for the coarse aggregate specific gravity testing without further study of test method deviations. However, the bias observed between the AASHTO T84 and AASHTO T209 is within or slightly above the multi-laboratory (d2s) limit which suggest that Corelok testing could be used instead of the traditional testing. However, it is recommended that these test methods are not used interchangeably within a project.

The current pavement target in-place density of 92% of MSG for the full pay allows more than 39% of the pavements produced in Indiana to have more than 8% air voids content and thus being water permeable. To reduce the high air void content and assure impermeable pavement it is recommended that a lower in-place target density for the full pay range is established.

Based on the overall variation of 0.93% the SGC pill air voids content values ranged from 0 to 7%. Then, statistically about 26% of the compacted pills had lower than 3% air voids content, and about 7% of the pills had higher than 5% air voids content. It is very unlikely that the production variation including raw material variation can explain such a large variation of the compacted mixture properties. Therefore, it is possible that there are other factors, which are contributing to the variation, such as moisture in the mix, variation in gyratory compaction temperature, poorly calibrated gyratory, reheating of the mixture, etc. Therefore it is recommended that before applying any changes to the current specification limits a more thorough investigation of the causes of air voids variation is conducted.

<u>PCC Production</u>

Based on the study findings, it was observed that both the INDOT and contractor testing protocols had variation that was essentially equal to or lower than those identified in the corresponding ASTM and AASHTO standards. This demonstrates that high quality testing is commonly performed in the state of Indiana and illustrates clear benefits of the technician certification programs and INDOT educational and training procedures.

The data indicates that while INDOT and the contractors had a low testing variation the total variation could vary significantly from project to project. This implies that different contractors implement and utilize different quality control practices. It is recommended that INDOT work with contractors to develop an incentive plan that encourages contractors to have improved consistency. Life-cycle simulations can be used to demonstrate that improved consistency results in improved long-term performance of concrete pavements (PAVESPEC 2002). As such the INDOT is encouraged to reevaluate their pay factors for strength, air and thickness to offer incentives for contractors with reduced production variation. Further, INDOT is encouraged to consider additional non-destructive testing procedures that can be used to enable production variation to be measured more frequently on paving and superstructure projects. Discussions with INDOT personnel performing the thickness test indicated potential difficulties, especially in thick pavements, if the core is not taken directly perpendicular to the pavement surface. INDOT should consider the development of procedures to account for this difficulty considering possible modifications to the current testing procedures.

Based on the variation in aggregate properties over time it is recommended that INDOT consider procedures to encourage producers to use more frequent testing to determine accurate aggregate specific gravity and absorption parameters for performing mixture designs and quality control procedures.

Implementation

Implementation of the research includes assessing the current pay factor limits and their correctness against the obtained testing and production variation. This can be done by comparing production variation and total variation to the acceptable testing variation limits.

Generally, the AASHTO/ASTM test method precision statements provide information about the minimum variability that INDOT should specify. The testing variation can be plotted as a function of production variation. As expected, the testing variation is constant irrespective of the production variation that may be experienced. The total overall variation is similar to the testing variation at low production levels; however, when high production variation is experienced the total variation becomes very similar to the production variation. Between low and high production variation the total variation is higher than both the testing and production variation.

It would be logical for INDOT to expect the contractor to have some production variation; therefore a target range of variation could be considered that would include some production variation and testing variation. It should be noted however that INDOT would want to discourage contractors from having high production variation. To encourage contractors to improve their process control INDOT could institute a penalty range for high levels of production and total variation. If INDOT chooses to reward the contractor for a high level of production control an incentive range could be imagined for production ranges below the target range. It should however be noted that minimizing the total variation should be rewarded only to a certain level after which time any variation that is measured is likely attributed nearly completely to testing variation.

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16. Abstract

This study was designed to analyze the variability associated with several test procedures used by the Indiana Department of Transportation (INDOT) in their Hot Mix Asphalt (HMA), portland cement concrete pavement (PCCP), and superstructure concrete protocols. The aim of this work was to document the variability associated with each of these test procedures toward application of this information of the development of acceptance criteria, pay factors, and pay incentives and disincentives.

The studied parameters for HMA production included the air void content and VMA of the gyratory compacted mixture, in-place density, binder (asphalt) content, aggregate bulk specific gravity and water absorption, bulk specific gravity of compacted mixture, and theoretical maximum specific gravity. The analysis of existing INDOT test data and additional Purdue laboratory study indicated that testing variation was within or only slightly above the (1s) AASHTO limits for testing variation. The production variation ranged from 50 to 85% of the total variation depending on the tested parameter.

The quality characteristics related to the acceptance program for PCC pavements and superstructure, which were investigated in this study, were plastic air content, flexural strength, and pavement thickness. Aggregate moisture and bulk specific gravity properties were also studied to determine what variations might be expected from a particular source. In addition to the QC/QA properties, compressive strength and split tensile strength of concrete were also studied. Based on the analysis of existing INDOT test data, it was found that all of the testing was within or only slightly above the (1s) AASHTO/ASTM testing variations. The production variation was found to range widely depending on the project.

Overall, the study demonstrates that high quality testing is commonly performed in the state of Indiana and illustrates clear benefits of the technician certification programs and INDOT educational and training procedures.

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ABSTRACT

This study was designed to analyze the variability associated with several test procedures used by the Indiana Department of Transportation in their Hot Mix Asphalt (HMA), portland cement concrete pavement (PCCP), and superstructure concrete protocols. The aim of this work was to document the variability associated with each of these test procedures toward application of this information of the development of acceptance criteria, pay factors, and pay incentives and disincentives.

The studied parameters for HMA production included the air void content and VMA of the gyratory compacted mixture, in-place density, binder (asphalt) content, aggregate bulk specific gravity and water absorption, bulk specific gravity of compacted mixture, and theoretical maximum specific gravity. The analysis of existing INDOT test data and additional Purdue laboratory study indicated that testing variation was within or only slightly above the (1s) AASHTO limits for testing variation. The production variation ranged from 50 to 85% of the total variation depending on the tested parameter.

The quality characteristics related to the acceptance program for PCC pavements and superstructure, which were investigated in this study, were plastic air content, flexural strength, and pavement thickness. Aggregate moisture and bulk specific gravity properties were also studied to determine what variations might be expected from a particular source. In addition to the QC/QA properties, compressive strength and split tensile strength of concrete were also studied. Based on the analysis of existing INDOT test data, it was found that all of the testing was within or only slightly above the (1s) AASHTO/ASTM testing variations. The production variation was found to range widely depending on the project.

Overall, the study demonstrates that high quality testing is commonly performed in the state of Indiana and illustrates clear benefits of the technician certification programs and INDOT educational and training procedures.

1 INTRODUCTION

1.1 Background

In recent years, the Indiana Department of Transportation (INDOT) has championed the use of innovative specifications for the construction of concrete pavements and structures. INDOT has been a lead state in promoting improved construction quality through the introduction of Quality Control/Quality Assurance specifications (QC/QA) and performance related specifications (PRS) (Nantung et al., 1999; Weiss et al., 1999; Hoerner et al., 1999). These specifications have a great potential to improve the consistency of asphalt and concrete construction by requiring the contractor to develop a better understanding of the level of variability that can be expected during production. Increasingly pay incentives and disincentives are being related to both the average test results that are obtained during quality assurance testing as well as the variability associated with these values. As a result, the INDOT must fully be aware of the expected variability that can be associated with each of the acceptance tests since they will not only be used for acceptance but they may also be used for pay adjustment.

Current QC/QA construction specifications in Indiana pay incentives and disincentives based on the quality of the product supplied. While it is anticipated that the current versions of the QC/QA programs will develop substantially over the next decade, it should be noted that each specification requires that the quality of the 'as-built' structure can be measured with an accuracy that is greater than the resolution used in determining pay adjustments. Therefore it is critical that the accuracy of the test methods used for determining these quality parameters can be measured and quantified before pay scales are determined.

Research has indicated (Hand and Epps, 2000) that the allowed variability in the materials testing can lead to unacceptable variation of the calculated quantities computed from the acceptable test results. Based on Monte Carlo simulation, the allowed variation in the tested bulk and theoretical maximum specific gravity values for asphalt concrete mixtures could produce unacceptable air void content variation. This may cause serious problems while trying to employ the performance-related specifications or volumetric acceptance programs, because the tested material seems to exceed the quality control and acceptance limits although it in reality might be within the limits, or vice versa. In addition, it has been shown that some indirect test methods may not provide an accuracy that is sufficient for determining pay factors (Graveen, 2000).

Testing variability is a combination of the variation associated with conducting the test and variability in the tested material. Typically, variability in the results can be reduced by using appropriate sampling procedures (i.e., obtaining and splitting the sample) which are important steps in the process of generating representative samples for material testing. A multi-laboratory analysis of production testing by D'Angelo et al. (2001) demonstrates that the Superpave Gyratory Compactor (SGC) variability can be greatly reduced by close adherence to standard sampling, splitting, and handling practices. Routine maintenance and calibration are also important in reducing variability.

A research conducted on field split sampling of Hot Mix Asphalt (HMA) (Schmitt et al., 2001) showed statistically significant bias between laboratories and also significant variation among individual tests. The study concluded that the variation that should be accounted for in the independent assurance and quality assurance construction specifications when making comparisons of the split samples.

In a study by Aschenbrener (1995), four HMA trial projects in Colorado DOT were constructed using an acceptance specification based on volumetric and strength properties of the mixture. The research pointed out several items that need to be checked to identify potential adjustment in mixture composition to account for changes that occur in the production through the plant. Research also suggested standard deviation values for the studied parameters that could be used in the acceptance program. These parameters were field compaction (density), air void content, Voids in the Mineral Aggregate (VMA), and binder content.

As the Colorado DOT study indicates, there are many places in the plant and lay down operations during field production where material related problems can develop, even though the mixture design prepared in the laboratory meets the specifications for performance and has been approved. Problems of this nature can arise from stockpiling, cold feed bins, baghouse fines, mixing and storage silo operations. An important element in the production is the field verification process, which verifies that the field produced HMA still meets the specifications for performance.

1.2 Problem Statement

Based on INDOT's experience, the repeatability of some of the test methods has been problematic. Some possible causes for the poor repeatability of the test results are: variability of tested material/property caused by manufacturing process; variability of tested material/property caused by poor sampling; testing conducted inadequately and not properly following test procedures; and an inadequate test procedure (accuracy). As a result, the precision of the test may not always be statistically valid and may be unacceptable for the determination of pay factors.

1.3 Objective of the Study

The objective of the work was to better understand the variability associated with the sampling and testing procedures of the selected INDOT test methods related to the QC/QA acceptance specifications for the HMA pavements, PCC pavements, and concrete superstructure elements. Specifically, for HMA QC/QA acceptance specifications this work focused on assessing the factors that contribute to the calculated volumetric quantities. The results of this study will improve the current specifications and readiness of the INDOT for implementing these properties in performance-related specifications in Indiana.

1.4 Scope and Limitations

The quality characteristics for the PCC pavements used in Indiana include concrete strength, slab thickness, air content, and pavement smoothness. The quality characteristics for the HMA volumetric acceptance specification used in Indian include binder content, air voids, VMA, density and smoothness of the constructed pavement.

The research concentrated not only on the material properties used in the QC/QA acceptance programs but also on some other properties such as test methods used for the appeal process. A major part of the research was conducted by statistically analyzing existing HMA and PCC test results provided by INDOT to assess the testing variability. This research did not include development of any new test methods.

The calculated volumetric quantities of the HMA that are included in the INDOT QC/QA acceptance program are the air void content of the gyratory compacted mixture, in-place density, and VMA. Research was concentrated on evaluating test methods and testing variability associated with the volumetric quantities including:

- Binder (asphalt) content,
- Aggregate bulk specific gravity and water absorption,
- Bulk specific gravity of compacted mixture, and
- Theoretical maximum specific gravity.

The quality characteristics related to the acceptance program of PCC pavements, which were investigated in this study, were:

- Plastic air content,
- Flexural strength,
- Pavement thickness.

Aggregate moisture and bulk specific gravity properties were also studied to determine what variations may be expected from a particular source. In addition to the QA properties, unit weight, plastic air content, compressive strength and split tensile strength of concrete were also studied due to their importance in superstructure concrete.

1.5 Research Approach and Report Organization

The research was divided into two parts. The first part was a statistical analysis of the existing INDOT test data, and the second part was a laboratory study of repeatability of selected test methods based on part one. The report is organized to present the HMA analysis results followed by the PCC analysis results.

2 REVIEW OF STATISTICAL TERMINOLOGY

The objective of the research was to assess testing variability by first analyzing the existing INDOT test data. The analysis approach and conclusions are dependent on the allowable variation (precision) established for each test method. This section provides a review of the statistical terminology and basic equations that were used in the report.

2.1 Precision and Bias

The sources of variability in the realization of a test method according to the standard practice procedures of American Society of Testing and Materials (ASTM): ASTM E177 "*Use of Terms Precision and Bias in ASTM Test Methods*" are operator, apparatus, environment, sample (sampling), and time. The variability may include systematical as well as random components. The systematic components may be evaluated if an accepted reference value is available.

The following definitions for precision, bias, accuracy, repeatability and reproducibility have been reproduced from ASTM E456: "*Standard Terminology for Relating to Quality and Statistics"* and ASTM E177. The relationships among bias, precision, and accuracy are illustrated in Figure 1.

Precision

The closeness of agreement between independent test results obtained under stipulated conditions.

Bias

The difference between the expectation of the test results and an accepted reference value.

Accuracy

The closeness of agreement between a test result and an accepted reference value. The term accuracy, when applied to a set of test results, involves a combination of a random component and of a common systematic error or bias component.

Repeatability

Precision under repeatability conditions. Repeatability conditions: conditions where independent test results are obtained with the same method on identical test items in *the same laboratory by the same operator using the same equipment within short intervals of time.*

<u>*Reproducibility*</u>

Precision under reproducibility conditions. Reproducibility conditions: conditions where test results are obtained with the same method on identical test items in different laboratories with different operators using different equipment.

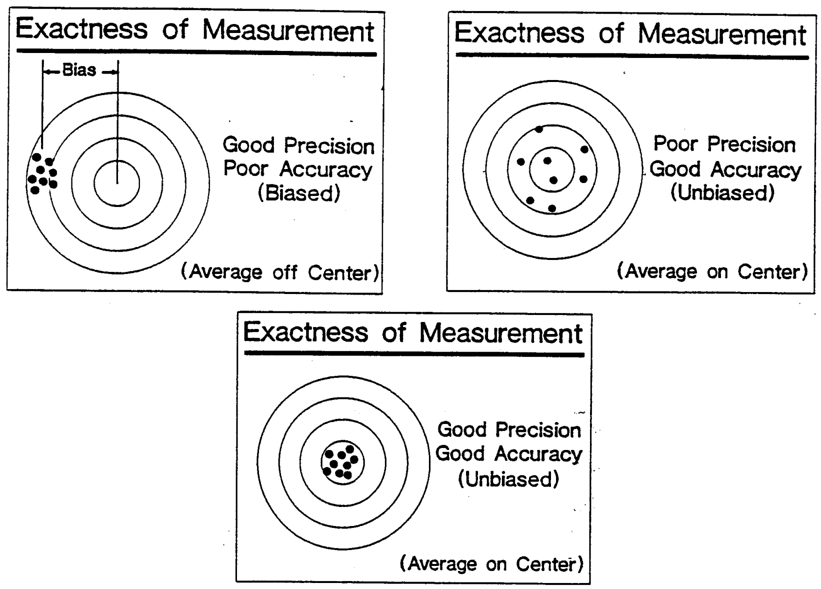

Figure 1. Relationships among bias, precision, and accuracy.

The precision and bias statements given in the standard test methods by the American Association of State Highway and Transportation Officials (AASHTO) and ASTM are an important measure of variability in testing of materials. However, not all of the test methods have these statements developed. The two precision statements, single-operator one-sigma limit and multi-laboratory one-sigma limit are related to within and between laboratory standard deviations (one-sigma limit) and they are defined according to the ASTM E456 and ASTM C670 "*Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials*".

<u>*One-sigma limit (1s)*</u>

The fundamental statistic underlying all indexes of precision is the standard deviation of the population of measurements characteristic of the test method when the latter is applied under specifically prescribed conditions (a given system of causes).

Single-operator one-sigma limit (1s)

The one-sigma limit for single-operator precision is a quantitative estimate of the variability of a large group of individual test results when the tests have been made on the same material by a single-operator using the same apparatus in the same laboratory over a relatively short period of time. This statistic is the basic one used to calculate the single-operator index of precision given in the precision statement for guidance of the operator.

Multi-laboratory one-sigma limit (1s)

The one-sigma limit for multi-laboratory precision is a quantitative estimate of the variability of a large group of individual test results when each test has been made in a different laboratory and every effort has been made to make the test portions of the material as nearly identical as possible. Under normal circumstances the estimates of one-sigma limit for multi-laboratory precision are larger than those for single-operator precision, because different operators and different apparatus are being used in different laboratories for which the environment may be different.

One-sigma limit in percent (1s%)

In some cases the coefficient of variation is used in place of the standard deviation as the fundamental statistic. This statistic is termed the "one-sigma limit in percent" (abbreviated (1s%)) and is the appropriate standard deviation (1s) divided by the average of the measurements and expressed as a percent.

Note that multi-operator one-sigma limit (1s or 1s%) is specified for many PCC properties instead of or in addition to the single-operator one-sigma precision.

Another possible index for the precision in addition to the standard deviation is the difference "two" standard deviation limits (d2s) or 95% limit (refer to the confidence interval on page 24) on differences between two test results according to ASTM 177 and ASTM C670:

Acceptable difference between two results (D2S)

The "difference two-sigma limit (d2s)" has been selected as the appropriate index of precision in most precision statements. These indexes indicate a maximum acceptable difference between two results obtained on test portions of the same material under the applicable system of causes.

Acceptable range of more than two results

In cases where the test method calls for more than two test results to be obtained, the range (difference between highest and lowest) of the group of test results must be compared to a maximum acceptable range for the applicable system of causes and number of test results. The range for different numbers of test results including two that would be equaled or exceeded in only 1 case in 20 is obtained by multiplying the appropriate *standard deviation (1s) or coefficient of variation (1s%) by the appropriate factor from the second column of Table 1*

Table 1. Maximum Acceptable Range.

Number of Test Results	**Multiplier of (1s) or (1s%) for Maximum Acceptable Range**
2	2.8
3	3.3
4	3.6
5	3.9
6	4.0
7	4.2
8	4.3
9	4.4
10	4.5

Note that multi-operator acceptable difference (d2s or d2s%) is specified for many PCC properties instead of or in addition to the single-operator acceptable difference.

The number of tests run must be taken into account when evaluating testing variation. Based on ASTM C670, usually the statistics used in evaluating precision and the indices of them are based on population distribution of single test results.

Single test result

When this is the case, the index of precision may be used in comparing single tests results only, not averages of two or more tests.

Test results based on averages

If the precision statement is based on test results that are averages of two or more measurements, then the number of measurements averaged must be stated, and in using the index of precision, averages of exactly that number of measurements must be used.

Precision of individual measurements averaged to obtain a test result

When two or more measurements are averaged to obtain a test result, the range of the individual measurements may be examined to determine whether the latter meet the criterion of being valid individual measurements under the conditions of the test method. The maximum acceptable range for individual measurements is obtained by multiplying the appropriate standard deviation (1s) or, coefficient of variation (1s%) obtained from averages by the appropriate factor from the second column of Table 2

Table 2.Maximum Acceptable Range of Individual Measurements

Number of Measurements Averaged to Obtain a Test Result	**Multiplier of (1s) or (1s%) for Averages to Obtain Maximum Acceptable Range of Individual Measurements**
2	3.9
3	5.7
4	7.3
5	8.6
6	9.9
7	11.0
8	12.1
9	13.2
10	14.1

Multi-laboratory precision expressed as a maximum allowable difference between two averages

When the test method calls for the reporting of more than one test result, multi-laboratory precision may be expressed as a maximum allowable difference between averages of such groups, one from each laboratory, and both the (d2s) or (d2s%) limit for individual results and this maximum allowable difference of two averages may be included in the multi-laboratory precision statement. The maximum allowable difference for averages of a given number of test results, n, is obtained by dividing the appropriate (d2s) or (d2s%) limit by the square root of n.

Combinations of sources of variability include within and between laboratory precisions. According to the ASTM E177 the within laboratory precision can be obtained in at least three experimental situations and it refers to the repeatability and laboratory bias:

- Precision from an experiment involving one operator, day, and apparatus
- Precision from repeated experiments within a laboratory
- Precision from within-laboratory experiments in several laboratories

Between laboratory precision refers to the reproducibility and bias of the test method and it is obtained by comparing several laboratories, each with its own operator, apparatus, and environmental conditions, obtaining a test result in randomly-selected specimens from the same reasonably-uniform sample of material.

2.2 Basic Statistical Concepts

Some basic statistical concepts (ASTM E456; McCuen, 1985) which were employed in this report are presented below. The basic form of statistical evaluation of test results is to use descriptive statistics that include computing mean, variance, standard deviation, standard error, and coefficient of variation. These parameters can be linked to sample or population statistics in normally distributed data:

Population is the totality of measurements.

Sample is a set of values that constitute a part of the population.

Sample size (n) is the number of units in a sample or the number of observation in a sample.

Mean identifies the center of mass for the values in the data set (population or sample) where $\bar{x}$ is the mean of samples $x_{1,n}$ and n is the number of samples:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{1}$$

Variance is a measure of the squared dispersion of observed values or measurements expressed as a function of the sum of the squared deviations from the population mean or sample average. The variance of the population is denoted as σ^2, and the variance of the sample is denoted as s^2. An unbiased estimate of variance is given by:

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2 \tag{2}$$

Pooled Variance is the average variance of the data groups (or samples) in a similar manner as the weighted average (mean) and it is computed as follows:

$$s^2_{pooled} = \frac{(n_1-1)s_1^2 + (n_2-1)s_2^2 + \cdots + (n_m-1)s_m^2}{n_1 + n_2 + \cdots + n_m - m} \tag{3}$$

Standard Deviation (for a sample) is the most usual measure of the dispersion of observed values or results expressed as the positive square root of the variance:

$$s = \sqrt{s^2} \tag{4}$$

Coefficient of variation (percent) is the standard deviation of the data set divided by the mean of the data set. Since the coefficient of variation is dimensionless, it can be used to compare variability among different measurements.

$$CV\,\% = \frac{s}{\overline{x}} \cdot 100 \tag{5}$$

Standard error of mean is defined as the standard deviation of errors around the mean and it has the same units as independent variable. Standard error is dependent of the number of samples as follows:

$$Se = \frac{s}{\sqrt{n}} \tag{6}$$

Confidence Interval for the mean (of unknown standard deviation σ of population) is calculated using *t* statistics. The measure of dispersion is given by standard error of mean $s/\sqrt{n}$ as a dispersion, and $t_{\alpha/2}$ is a value of random variable having a *t* distribution with $\upsilon = n$-1. Equation (7) gives a two sided confidence interval for mean.

$$\overline{x} \pm t_{\alpha/2}\left(\frac{s}{\sqrt{n}}\right) \tag{7}$$

3 INDOT QC/QA SPECIFICATIONS

The INDOT QC/QA specifications place the responsibility for quality control on the contractor, while the state assumes responsibility for quality assurance and acceptance. Specifications are statistically based utilizing methods such as random sampling and lot-by-lot testing. Usually lots are divided into sublots and testing is conducted by sublot bases. The final acceptance is conducted by the lot or sublot bases.

3.1 HMA QC/QA Specifications (Section 401)

The following tables and equations have been reproduced from Indiana Department of Transportation 1999 Standard Specification Book, Section 401 – Quality Control/Quality Assurance, QC/QA, Hot Mix Asphalt, HMA, Pavement. The specification referred to is effective on or after March 1, 2004.

It should be noted that only the text applicable for this research has been reproduced for the following discussion and the full specification needs to be retrieved from the original source. Therefore, specifications such as smoothness specifications are not discussed because they are not included in this study. The numbering used in the specifications is shown in the beginning of each discussed item to make it easier to retrieve the original specification text.

The test methods discussed in the specifications are based on the standards given by AASHTO, ASTM, and Indiana Test Methods and Procedures (ITM). The description of the relevant AASHTO and ASTM test methods are given in Chapter 4. Because only few of the ITM test methods mentioned in the following sections are studied and discussed later on, the title of the method is presented in parenthesis after the method number to make it easier for the reader to follow the specification text.

3.1.1 Acceptance of Mixtures

401.01 Description. These specifications are applicable for the work that shall consist of one or more courses of QC/QA HMA base, intermediate, or surface mixtures constructed on prepared foundations.

401.07 Lots and Sublots. Lots will be defined as 4000 Mg (4000 t) of base or intermediate mixtures or 2400 Mg (2400 t) of surface mixture. Lots will be further sub divided into sublots not to exceed 1000 Mg (1000 t) of base or intermediate mixtures or 600 Mg (600 t) of surface mixture. Partial sublots of 100 Mg (100 t) or less will be added to the previous sublot. Partial sublots greater than 100 Mg (100 t) constitute a full sublot.

401.09 Acceptance of Mixtures. Acceptance of QC/QA HMA mixtures for binder content, VMA at N_{des}, and air voids at N_{des} for each lot will be based on tests performed by the INDOT Engineer. Acceptance testing for surface mixtures will include tests for moisture content. The Engineer will randomly select the location(s) within each sublot for sampling in accordance with the ITM 802 (Random Sampling).

An acceptance sample will consist of two plate samples with the first (X) being at the random location and the second (X) 0.6 m (2 ft) ahead station. A backup sample (Z) consisting of two plate samples shall be located 0.6 m (2 ft) towards the center of the mat from the acceptance sample. For surface mixtures, an additional sample shall be located 0.6 m (2 ft) back station from the random sample location.

Samples from each location shall be obtained from each sublot from the pavement in accordance with ITM 580 (Sampling HMA). The plate sampling scheme is illustrated in Figure 2.

The binder content will be determined in accordance with ITM 586 (Binder Content by Ignition) or ITM 571 (Quantitative Extraction of Asphalt/Binder and Gradation of Extracted Aggregate from HMA Mixtures) as directed by the Engineer. The maximum specific gravity will be determined in accordance with AASHTO T 209. The Air Voids and VMA will be determined in accordance with AASHTO PP 28 based on the average bulk specific gravity from two gyratory specimens. The gyratory pills will be prepared in accordance with AASHTO T 312.

The bulk specific gravity of gyratory specimens for dense graded mixtures will be determined in accordance with AASHTO T 166.

The mixture properties for each sublot shall meet the requirements for the tolerances from the JMF. Acceptance of mixtures for air voids, binder content, and VMA are summarized in Table 3. Air voids, binder content and VMA values will be reported to the nearest 0.1%.

Table 3. INDOT HMA Mixture Acceptance Tolerances (for sublot samples).

ACCEPTANCE TOLERANCES	
MIXTURE PROPERTIES	TOLERANCES FROM JMF
DENSE GRADED	
Air Voids	JMF ± 1.0 %
Binder Content	JMF ± 0.5 %
VMA	JMF ± 1.0 %
OPEN GRADED	
Air Voids *	JMF ± 3.0 %
Binder Content	JMF ± 0.5 %

* G_{mb} will be determined in accordance with ASTM D 6752

In the event that an acceptance sample is not available to represent a sublot(s), all test results of the previous sublot will be used for acceptance. If the previous sublot is not available, the subsequent sublot will be used for acceptance.

3.1.2 Construction Requirements

401.16 Density. Acceptance of pavement density will be based on lots and sublots in accordance with 401.07.

Density of the compacted dense graded mixture will be determined from cores. Density acceptance by cores will be based on samples obtained from two random locations selected by the Engineer within each sublot in accordance with ITM 802 (Random sampling). One core shall be cut at each random location in accordance with ITM 580 (Sampling HMA). The transverse core location will be located so that the edge of the core will be no closer than 75 mm (3 in.) from a confined edge or 150 mm (6 in.) from a non-confined edge of the course being placed. The maximum specific gravity will be determined from the sample obtained in 401.09.

The density for the mixture will be expressed as the percentage of maximum specific gravity (%MSG) obtained by dividing the average bulk specific gravity by the maximum specific gravity for the sublot, times 100. The Engineer will determine the BSG of the cores in accordance with AASHTO T 166. The maximum specific gravity will be determined in accordance with AASHTO T 209 from samples prepared in accordance with ITM 572 (Drying HMA Mixtures). The target value for density of dense graded mixtures of each sublot shall be 92.0%.

The test results for each sublot shall meet the requirements for the tolerances as shown in the Table 4:

Table 4. Tolerance for Density.

DENSE GRADED ACCEPTANCE TOLERANCE	
Core Density	94.0 ± 2.0 %MSG

The Engineer's acceptance test results for each sublot will be available when the testing is complete. Acceptance of the pavement for density (%MSG) will be reported to the nearest 0.1%.

3.1.3 Pay Factors

401.19 Pay Factors. A composite pay factor for each sublot based on test results for mixture properties and density is determined in a weighted formula as follows:

$$SCPF = 0.20(PF_{BINDER}) + 0.35(PF_{VOIDS}) + 0.10(PF_{VMA}) + 0.35(PF_{DENSITY}) \tag{8}$$

where:

SCPF = Sublot Composite Pay Factor for Mixture and Density

PF_{BINDER} = Sublot Pay Factor for Binder Content

PF_{VOIDS} = Sublot Pay Factor for Air Voids at N_{des}

PF_{VMA} = Sublot Pay Factor for VMA at N_{des}

$PF_{DENSITY}$ = Sublot Pay Factor for Density

If the SCPF for a sublot is less than 0.85, the Materials and Tests Division will evaluate the pavement. If the Contractor is not required to remove the mixture, quality assurance adjustments of the lot will be assessed or other corrective actions taken as determined by the Materials and Tests Division.

A lot pay factor (LPF) for mixture properties and density is determined by averaging the SCPF of a lot.

(a) Mixture. Sublot test results for mixture properties and density will be assigned pay factors in accordance with Tables 3, 4 and 5. The pay factors shall be rounded to the nearest 0.01.

Table 5. INDOT Pay Factors for Binder Content.

BINDER CONTENT	
Pay Factor	Deviation from JMF (± %)
1.05	≤ 0.2
1.04	> 0.2 and ≤ 0.3
1.02	> 0.3 and ≤ 0.4
1.00	> 0.4 and ≤ 0.5
0.95	> 0.5 and ≤ 0.6
0.90	> 0.6 and ≤ 0.7
0.85	> 0.7 and ≤ 0.8
0.85 – 0.05 per each 0.1% over 0.8%	> 0.8

Table 6. INDOT Pay Factors for VMA.

VMA	
Pay Factor	Deviation from JMF (± %)
DENSE GRADED	
1.05	≤ 0.5
1.00	> 0.5 and ≤ 1.0
0.95	> 1.0 and ≤ 1.5
0.90	> 1.5 and ≤ 2.0
0.85	> 2.0 and ≤ 2.5
0.85 – 0.02 per each 0.1% over 2.5%	> 2.5
OPEN GRADED	
1.00	All

Table 7. INDOT Pay Factors for Air Void Content.

AIR VOIDS	
Pay Factor	Deviation from JMF (± %)
DENSE GRADED	
1.05	≤ 0.5
1.00	> 0.5 and ≤ 1.0
0.95	> 1.0 and ≤ 1.5
0.85	> 1.5 and ≤ 2.0
Submitted to the Materials and Tests Division *	> 2.0
OPEN GRADED	
1.05	≤ 1.0
1.00	> 1.0 and ≤ 3.0
0.95	> 3.0 and ≤ 3.5
0.85	> 3.5 and ≤ 4.0
Submitted to the Materials and Tests Division *	> 4.0

*Test results will be considered and adjudicated as a failed material in accordance with normal Department practice as listed in 105.03.

For mixtures produced during a plant's adjustment period, pay factors based on the JMF with the above tolerances will be used to compute quality assurance adjustments.

(b) Density. Sublot test results for density will be assigned pay factors in accordance with Table 8.

Table 8. INDOT Pay Factors for Density.

Pay Factors– Percent	Percentages are based on %MSG	
	Dense Graded	Open Graded
Submitted to the Materials and Tests Division *	≥ 97.0	
1.05 - 0.01 for each 0.1 % above 95.6	95.6 – 96.9	
1.05	94.0 – 95.5	
1.00 + 0.005 for each 0.1% above 93.1	93.1 – 93.9	
1.00	92.0 – 93.0	84.0
1.00 - 0.003 for each 0.1 % below 92.0	91.0 – 91.9	
0.97 - 0.012 for each 0.1 % below 91.0	90.0 – 90.9	
0.85 - 0.015 for each 0.1 % below 90.0	89.0 – 89.9	
Submitted to the Materials and Tests Division *	≤ 88.9	

* Test results will be considered and adjudicated as a failed material in accordance with normal Department practice as listed in 105.03.

As the tables above show the contractor is getting bonuses if the measured quantity is well within the acceptable tolerance and penalties if the measured quantity exceeds the acceptable tolerances specified in Table 3 and Table 4. The total quality assurance adjustments are calculated adding mixture adjustments and smoothness adjustments.

401.20 Appeals. If the QC test results do not agree with the acceptance test results, a request, along with the QC test results, may be made in writing for additional testing. Additional testing may be requested for one or more of the following tests: MSG, BSG of the gyratory specimens, binder content, or BSG of the density cores. The request for the appeal for MSG, BSG of gyratory specimens, binder content or BSG of the density cores shall be submitted within seven calendar days of receipt of the Department's written results for that lot. The lot, sublot and specific test(s) shall be specified at the time of the appeal. Upon approval of the appeal, the Engineer will perform additional testing as follows:

The backup or new sample(s) will be tested in accordance with the applicable test method for the test requested.

3.2 PCC QC/QA Specifications (Section 501)

The following tables and equations have been reproduced from Indiana Department of Transportation 1999 Standard Specifications, Section 501 – Quality Control/Quality Assurance, QC/QA, Portland Cement Concrete Pavement, PCCP. The specification referred to is effective on or after March 1, 2004.

3.2.1 Construction Requirements and Tolerance for Acceptance

501.01 Description. These specifications are defined for the work consisting of QC/QA Portland cement concrete pavement, PCCP, placed on a prepared subgrade or subbase.

501.07 Lots and Sublots. Lots will be defined as 6000 m^2 (7,200 syd) of PCCP. Lots will be further subdivided into sublots of 2000 m^2 (2,400 syd) of PCCP within a lot. Partial sublots of 400 m^2 (480 syd) or less will be added to the previous sublot. Partial sublots greater than 400 m^2 (480 syd) constitute a full sublot. Partial lots of one or two sublots constitute a full lot.

501.08 Acceptance. Acceptance of PCCP for flexural strength, air content, unit mass (weight), water/cementitious ratio, and thickness will be determined on the basis of tests performed by the Engineer. The Engineer will randomly select the location within each sublot for sampling in accordance with ITM 802 (Random Sampling).

The random sample(s) per sublot shall be of sufficient quantity to perform all required tests and obtained in accordance with AASHTO T 141. Concrete and necessary labor for sampling shall be furnished as required by the Engineer. The test results of the sublots for each lot will be averaged and shall be in accordance with 501.05 and 501.06, except the lot average for thickness shall be in accordance with 501.26. Test results are to be shared in a timely manner. Table 9 gives the frequency of testing and test methods used for the acceptance.

Table 9. Frequency of acceptance testing and precision used.

Test or Determination	Frequency	Test Method	Precision
7-Day Flexural Strength*	Two beams per sublot	AASHTO T 97	10 kPa (1 psi)
Air Content*	One per sublot	AASHTO T 152 or ASTM C 173	0.1
Unit Weight	One per sublot	AASHTO T 121	1
Water/Cementitious Ratio	Once per week	ITM 403	0.001
Thickness*	Two per sublot	ITM 404	0.1

*Used as a pay-factor

501.26 Pavement Thickness. PCCP thickness shall be determined after all corrective grinding. The Contractor shall obtain cores at the locations determined by the Engineer in accordance with ITM 802 (Random Sampling). Cores, 100 mm (4 in.) in diameter, shall be taken in the presence of the Engineer for the full depth of the PCCP. The Engineer will take immediate possession of the cores. Cores shall not be taken within 150 mm (6 in.) of the edge of pavement, within 75 mm (3 in.) of longitudinal joints, within 0.6 m (2 ft) of D-1 contraction joints, or within 1.5 m (5 ft) of a transverse construction joint. Cores shall be taken and measured in accordance with ITM 404 (PCCP Core Length Determination).

The width of adjudicated PCCP shall be the width of pavement lane in which the deficiency occurs. Pavement that has been replaced shall be investigated for thickness.

The thickness of the PCCP for each sublot shall be the average lengths of both cores from the sublot. Calculations shall be to the nearest 2.5 mm (0.1 in.).

501.27 Tolerance. Plastic unit weight, water/cementitious ratio, flexural beam, and air content tests will be performed during PCCP operations. The tolerances of INDOT acceptance tests are:

(a) Plastic Unit Weight. Sublots shall not vary by more than ±3.0% from the target unit weight. A stop paving order will be issued if the plastic unit weight exceeds ±3.0% from the target plastic unit weight.

(b) Water to Cementitious Ratio. The weekly water to total cementitious materials ratio shall not vary more than ±0.030 of the target value or exceed 0.450.

(c) Flexural Strength. Average lot values of 4000 kPa (570 psi) and above shall be achieved.

(d) Air Content. The average lot air content values should not vary more than -0.8% to +2.4% from the 6.5% target air content. The range of sublot air content values shall not exceed 2.5%.

3.2.2 Pay Factors

501.28 Pay Factors. When the PCCP test results for flexural strength, plastic air content, air content range, smoothness, and thickness exceed the allowable tolerances, pay factors will be determined. The pay factors will be used to calculate a quality assurance adjustment quantity for the lot. For this report the pay factors for smoothness are not considered.

The adjustment for flexural strength, plastic air content, air content range, thickness and smoothness will be calculated as follows:

$$q = L \text{ x } U \text{ x } (P - 1.00) \tag{9}$$

where:

q = quality assurance adjustment quantity

L = lot quantity

U = unit price for QC/QA-PCCP, $\$/m^2$ ($\$/yd^2$)

P = pay factor

For sublot thickness determination:

$$qT = lT \text{ x } U \text{ x } (P - 1.00) \tag{10}$$

where:

q_T = quality assurance adjustment quantity

l_T = sublot quantity for thickness

U = unit price for QC/QA-PCCP, \$/m^2 (\$/yd^2)

P = Pay Factor

(a) Flexural Strength. When test results for flexural strength exceed the allowable tolerance, a pay factor will be assessed for lots and sublots. Pay factors for lot average flexural strength are summarized in Table 10. If a sublot value is less than 3500 kPa (500 psi), the PCCP will be adjudicated as a failed material in accordance with normal Department practice as listed in 105.03. For a sublot completely removed, the sublot test value from the replacement sublot will replace the original test value.

Table 10 Pay Factors for Flexural Strength

Lot Average Flexural Strength	
kPa (psi)	Pay Factors
3927 (570) and Above	1.00
3893 - 3926 (565 - 569)	0.98
3858 - 3892 (560 - 564)	0.96
3824 - 3857 (555 - 559)	0.94
3789 - 3823 (550 - 554)	0.92
3755 - 3788 (545 - 549)	0.89
3720 - 3754 (540 - 544)	0.86
3686 - 3719 (535 - 539)	0.83
3617 - 3685 (525 - 534)	0.78
3548 - 3616 (515 - 524)	0.72
3547 (514) or less	*

* The PCCP will be adjudicated as a failed material in accordance with normal Department practice as listed in 105.03. The PCCP may be subject to removal and replacement or left in place with reduced or no payment.

(b) Air Content. When test results for air content exceed the allowable tolerance or range, a pay factor will be assessed for lots and sublots. Pay factors for lot average plastic air content are summarized in Table 11. If a sublot value is less than 4.0% or greater than 10.0%, the PCCP will be adjudicated as a failed material in accordance with normal Department practice in accordance with 105.03. For a sublot completely removed, the sublot test value from the replacement sublot will replace the original test value.

Table 11 Pay Factors for Plastic Air Content

Lot Average Air Content	
Percent %	Pay Factors
> 10.0	*
10.0	0.80
9.7 - 9.9	0.85
9.5 - 9.6	0.91
9.3 - 9.4	0.96
9.0 - 9.2	0.98
5.7 - 8.9	1.00
5.0 - 5.6	0.99
4.7 - 4.9	0.98
4.6	0.88
4.5	0.80
< 4.5	*

* The PCCP will be adjudicated as a failed material in accordance with normal Department practice as listed in 105.03. The PCCP may be subject to removal and replacement or left in place with reduced or no payment.

Lot Range for Air Content	
Percent %	Pay Factors
0.0 - 2.5	1.00
2.6 - 3.0	0.99
3.1 - 3.5	0.97
> 3.5	*

* The PCCP will be adjudicated as a failed material in accordance with normal Department practice as listed in 105.03. The PCCP may be subject to removal and replacement or left in place with reduced or no payment.

(c) Thickness. When test results for pavement thickness do not meet the specified thickness, a pay factor will be assessed for sublots. Sublot pay factors for pavement thickness are summarized in Table 12.

The total quality adjustments are calculated by adding the material adjustment and smoothness adjustment points.

501.29 Appeals. If the Contractor does not agree with the acceptance test results, a request may be made in writing for additional tests for a sublot(s) or lot. The basis of the appeal shall include applicable QC test results showing acceptable quality results and shall be submitted within five calendar days of receipt of the Department's written results for that lot. Upon review of the appeal, the Engineer may accept the PCCP in accordance with 105.03 or accept the appeal.

Table 12 Pay Factors for Pavement Thickness

Sublot Pay Factors For Thickness Average Core Depth (ACD) Design Depth (DD)	
ACD Minus DD	Pay Factor
> +13 mm (> +0.5 in.)	1.05
+7 mm to +13 mm (+0.3 in. to +0.5 in.)	1.02
± 6 mm (0.2 in.)	1.00
-6 mm to -13 mm (-0.3 in. to -0.5 in.)	0.96
- 14 mm to -19 mm (-0.6 in. to -0.7 in.)	0.90
- 20 mm to -25 mm (-0.8 in. to -1.0 in.)	0.80
< -25 mm (< -1.00 in.)	*

(a) Flexural Strength. Appeals will not be considered unless QC test results indicate greater than a 350 kPa (50 psi) difference between the Department's and the Contractor's tests. Upon approval for the additional testing, the Contractor shall obtain cores, as directed, in the presence of the Engineer.

(a) Flexural Strength. Appeals will not be considered unless QC test results indicate greater than a 350 kPa (50 psi) difference between the Department's and the Contractor's tests. Upon approval for the additional testing, the Contractor shall obtain cores, as directed, in the presence of the Engineer.

Each core will be tested for split tensile strength in accordance with ASTM C 496. The cores will be submerged in lime saturated water prior to testing for a minimum of 40 h.

The average core split tensile strength will be determined for the appealed and adjacent sublots. Flexural strength will be calculated as follows.

$$F_D = S_D \times \left[\frac{F_{A1}}{2S_{A1}} + \frac{F_{A2}}{2S_{A2}} \right] \tag{11}$$

where:

F_D = flexural strength of the appealed sublot

F_{A1} = flexural strength of the previous adjacent sublot

F_{A2} = flexural strength of the subsequent adjacent sublot

S_D = split tensile strength of the appealed sublot

S_{A1} = split tensile strength of the previous adjacent sublot

S_{A2} = split tensile strength of the subsequent adjacent sublot

(b) Air Content. Appeals will not be considered unless QC test results indicate greater than a 0.5 percent difference between the Department's and the Contractor's tests. Upon approval for the additional testing, the Contractor shall obtain core(s) as directed in the presence of the Engineer.

4 STUDIED INDOT TEST METHODS

4.1 HMA Test Methods

The INDOT test methods studied in this research are shown in Table 13. A short description of each test method is given below. These test methods are used directly or indirectly in the volumetric acceptance program for the HMA contacts (Section 401). Acceptance of mixtures is based on binder content, VMA at N_{des}, air voids at N_{des} and density of pavement. The acceptance of mixtures requires air void content and VMA to be determined according to AASHTO PP28, which includes the test methods of T166, T209, T84 and T85. Pavement density is measured using test methods T166 and T209.

The INDOT is using standard AASHTO test methods for most of the test. Only the binder content by ignition oven method is measured using INDOT's own Indiana Test Method ITM 586.

Table 13. Studied INDOT HMA test methods.

Test Method	**HMA Properties**	**Used in QA Acceptance**
AASHTO T84, (6.1.1)	Fine Aggregate Specific Gravity and Absorption	Yes, indirectly
AASHTO T85, (8.1)	Coarse Aggregate Specific Gravity and Absorption	Yes, indirectly
AASHTO T166	Bulk Specific Gravity of Compacted Bituminous Mixtures	Yes, indirectly
AASHTO T275	Bulk Specific Gravity of Compacted Bituminous Mixtures using Paraffin-Coated Specimens	Yes, indirectly
AAHTO T209	Theoretical Maximum Specific Gravity of Bituminous Mixtures	Yes, indirectly
ITM-586	Binder Content by Ignition	Yes

<u>AASHTO T84 –Specific Gravity and Absorption of Fine Aggregate</u>

This method covers the determination of bulk and apparent specific gravity, and absorption of fine aggregate. The specific gravity may be expressed as bulk specific gravity, G_{sb}, saturated-surface-dry (SSD) bulk specific gravity, SSD G_{sb}, or apparent specific gravity, G_{sa}. Fine aggregates are defined as 100% passing the 9.5 mm (3/8 in.) sieve and a minimum of 80% passing the 4.75 mm (No.4) sieve. Exception to the AASHTO T 84 is that the in-water mass (weight) shall be determined following the 15 h soaking period prior to determining the SSD mass.

In this test, the operator is required to obtain measurements of aggregate mass in three moisture conditions: oven dry, submerged in water, and at moisture state termed "saturated surface dry". The ovens dry and submerged in water determinations are relatively straightforward, but the determination of the SSD is relatively difficult and prone to errors.

AASHTO T85 –Specific Gravity and Absorption of Coarse Aggregate (Procedure 8.1)

This method covers the determination of specific gravity and absorption of coarse aggregate. The specific gravity may be expressed as bulk specific gravity, G_{sb}, saturated-surface-dry (SSD) bulk specific gravity, SSD G_{sb}, or apparent specific gravity, G_{sa}. Exception to the AASHTO T 85 is that the in-water mass (weight) shall be determined following the 15 h soaking period prior to determining the SSD mass. Coarse aggregates are defined as having a minimum of 20% retained on the 4.75 mm (No.4) sieve. Testing is conducted following the procedure 8.1 which includes drying aggregate to the constant mass before soaking.

AASHTO T166 – Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens

This test method covers the determination of bulk specific gravity of compacted bituminous mixtures, G_{mb}. This method should not be used with samples that contain open or interconnecting voids and/or absorption more than 2 percent of water by volume. Test method covers both the G_{mb} of gyratory compacted pills and cores obtained from the pavement.

AASHTO T275 –Bulk Specific Gravity of Compacted Bituminous Mixtures Using Paraffin-Coated Specimens

This test method covers the determination of bulk specific gravity of compacted bituminous mixtures, $G_{sb,}$ with high water absorption. Thus, this method should be used with samples that contain open or interconnecting voids and/or absorption more than 2 percent of water by volume. This test method is used with road cores that may have a high air void content and water absorption.

AASHTO T209 – Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures

This test method covers the determination of the theoretical maximum specific gravity and density of uncompacted (loose) bituminous paving mixtures, G_{mm}. The best precision is obtained when the procedure is run on samples that contain aggregates which are completely coated.

A supplemental procedure (Procedure 11) is needed if the pores of the aggregates are not thoroughly sealed by a bituminous film. This may imply testing mixture from the cores that contain uncoated cut aggregates faces. In the supplemental procedure the mixture is dried using an electrical fan to remove absorbed water from the aggregate.

ITM 586 – Binder Content by Ignition

This test method covers the determination of asphalt mixture binder content, P_b, by ignition in a furnace. The aggregate remaining after ignition may be used to evaluate the gradation of the aggregate in the mixture. The binder content of the mixture is based on the percent weight (mass) loss of a sample. The weight loss is comprised of a loss of binder and a loss of aggregate. A mixture calibration factor shall be determined for each mixture in a specific oven to account for any loss of aggregate during ignition and any variability between ovens that may occur. Each mixture calibration factor is unique to an individual ignition oven and it is not transferable.

4.2 PCC Test Methods

The studied INDOT test methods for the paving concrete mixture design criteria and construction properties are shown in Table 14 in addition to the test methods that are used for superstructure quality control. The table also shows what test methods are used in the PCCP QA acceptance procedure (Section 501). For the PCC mixtures and pavements, INDOT is using both the AASHTO and ASTM methods and INDOT's own ITM methods. The exceptions for the specified AASHTO and ASTM methods are given in the Indiana Department of Transportation 1999 Standard Specifications, Section 500 and Section 900.

For the coarse aggregate specific gravity (AASHTO T85) INDOT is using procedure 8.2 for concrete aggregates. In this procedure drying the aggregates to a constant mass is eliminated before soaking them in the water. For the fine aggregate specific gravity, the test is the same for both asphalt and concrete aggregates.

Table 14. Studied INDOT PCC test methods.

Test Methods	PCC Properties	Used in QA Acceptance	Paving Pay-Factor
AASHTO T84 (6.1.2)	Fine Aggregate Specific Gravity and Absorption	No	No
AASHTO T85 (8.2)	Coarse Aggregate Specific Gravity and Absorption	No	No
AASHTO T152	Air Content of Freshly Mixed Concrete using Pressure method	Yes	Yes
ASTM C173	Air Content of Freshly Mixed Concrete using the Volumetric Method	Yes	Yes
AASHTO T121	Unit weight (QC/Superstructure Acceptance)	Yes	No
AASHTO T97	7-day Flexural Strength	Yes	Yes
ASTM C496*	Splitting Tensile Strength (cylinders)	Appeal	No
ASTM C39	Compressive Strength of Cylindrical Specimens	Superstructure	No
ITM 404	PCCP Core Length Determination (Thickness of concrete)	Yes	Yes

* Appeal for flexural strength

AASHTO T152 –Air Content of Freshly Mixed Concrete by the Pressure Method

This method covers determination of the air content of freshly mixed concrete from observation of the change in volume of concrete with a change in pressure. The exceptions to AASHTO T152 for determining the air content in PCC shall be as follows:

1. The aggregate correction factor test shall be re-run for confirmation if the test results for gravel are greater than 0.4% or if the test results for crushed stone are greater than 0.6%.
2. For aggregates indicating a high correction factor, the aggregate may be washed from the concrete sample and used to determine the correction factor.

ASTM C173 – Air Content of Freshly Mixed Concrete by the Volumetric Method

This test method covers determination of the air content of freshly mixed concrete containing any type of aggregate, whether it is dense, cellular, or lightweight.

AASHTO T121 – Standard Method of Test for Mass per Cubic Meter (Cubic Foot), Yield, and Air Content (Gravimetric) of Concrete

The exceptions to AASHTO T121 for determining the unit weight of concrete shall be as follows:

1. A strike-off bar in accordance with AASHTO T 152 may be used in lieu of a strike-off plate.
2. Mass (weight) shall be determined to the nearest 0.005 kg (0.01 lb).

AASHTO T97 – Standard Method of Test for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)

This test method covers determination of flexural strength of concrete by the use of a simple beam with third-point loading. The exceptions to AASHTO T97 for conducting a flexural test on concrete beams shall be as follows:

1. The beam size shall be measured to the nearest 1.0 mm (1/16 in.).
2. The test result shall be discarded when the break occurs outside the middle third of the beam.

ASTM C496 – Splitting Tensile Strength of Cylindrical Concrete Specimens

This test method covers the determination of the splitting tensile strength of cylindrical concrete specimens, such as molded cylinders and drilled cores. This test method is used for appeal for flexural strength in case QC test results indicate greater than a 350 kPa (50 psi) difference between the Department's and the Contractor's tests. The cores will be submerged in lime saturated water prior to testing for a minimum of 40 h.

ASTM C39 – Compressive Strength of Cylindrical Concrete Specimens

This test method covers determination of compressive strength of cylindrical concrete specimens such as molded cylinders and drilled cores. It is limited to concrete having a unit weight in excess of 50 lb/ft^3 (800 kg/m^3).

ITM 404 – PCCP Core Length Determination

This test method covers the determination of PCCP core lengths to determine the thickness of PCCP. This test method refers to the AASHTO T24 Obtaining and Testing Drilled Cores and Sawed Beams of Concrete.

4.3 Precision Limits for Studied Test Methods

The precision or allowable variation of the test methods described above is based on the precision statements given in the test specifications. The precision statements for both the AASHTO and ASTM test methods for the studied material properties are given in Table 15, Table 16, and Table 17. These tables give the single-operator precision, multi-operator precision, and multi-laboratory precision, respectively. The terms single-operator, multi-operator and multi-laboratory precision have been defined in Chapter 2.

Two precision indices are given in the tables: the one-sigma limit (standard deviation) (1s), and acceptable difference between two test results “difference two-sigma limit” (d2s). The (1s%) and (d2s%) refer to the precision indices defined as coefficient of variation instead of standard deviation.

Most of the precision statements (indices) are given in the form of one-sigma standard deviation (1s) except for the mechanical testing of portland cement concrete properties, for which the precision is given in the form of coefficient of variation (1s%). This is because the variation is dependent on the strength of concrete.

The ITM methods are based on the AASHTO methods and the allowable precision specified in them. Therefore the ITM method and consequent AASHTO or ASTM method is presented together to indicate where the precision statement is derived.

It is important to note that the ASTM D2726 standard has a new precision statement in the version published in 2004. The limits are substantially lower than the previous limits and they are given separately for the 12.5-mm and 19.0mm nominal maximum size mixtures.

Table 15. Allowable variation of test results, single-operator precision.

Designations		Tested Parameter (Unit for (1s))	Single-operator Precision			
			Standard deviations (1s) or (1s%)		Acceptable range of two results (d2s) or (d2s%)	
AASHTO/ ITM Method	ASTM Method		AASHTO	ASTM	AASHTO	ASTM
T84	C 128	Fine aggr. G_{sb}	0.011	0.011	0.032	0.032
		SSD G_{sb}	0.0095	0.0095	0.027	0.027
		G_{sa}	0.0095	0.0095	0.027	0.027
		Water abs. (%)	0.11	0.11	0.31	0.31
T85	C 127	Coarse aggr. G_{sb}	0.009	0.009	0.025	0.025
		SSD G_{sb}	0.007	0.007	0.020	0.020
		G_{sa}	0.007	0.007	0.020	0.020
		Water abs. (%)	0.088	-	0.25	-
T166	D 2726	G_{mb}	*	0.0124 [c] 0.008[d] 0.013[e]	*	0.035[c] 0.023[d] 0.037[e]
T275	D 1188	G_{mb}	0.007[f]	0.028	0.020	0.079
T209	D 2041	G_{mm}	0.004	0.008	0.011	0.023
T209 Supplem.	-	G_{mm}	0.0064	0.0064	0.018	0.018
T308/ITM 586	-	P_b (%)	0.04	-	0.11	-
T152	C231	Air content (%)	*	*	*	*
T121	C138	Unit weight (lb/ft^3)	*	0.65	*	1.85
T97	C 78	Flexural Strength	*	5.7% [a]	*	16.0%[a]
-	C496	Tensile Strength	-	5.0% [a]	-	14.0%[a]
-	C39	Comp. Strength	-	2.37% [a,b]	-	6.6% [a,b]
ITM 403	-	W/C Ratio	*	-	*	-
ITM 404	-	Thickness	*	-	*	-

* Not determined, a) Coefficient of variation, b) Laboratory Conditions, c) Old specification (2000), d) New specification limit for 12.5-mm NMAS mix (2004), d) New specification limit for 19.0-mm NMAS mix, f) Calculated from (ds2) limit.

Table 16. Allowable variation of test results, multi-operator precision.

Designations		Tested Parameter (Unit for (1s))	Multi-operator Precision			
			Standard deviations (1s) or (1s%)		Acceptable range of two results (d2s) or (d2s%)	
AASHTO/ ITM Method	ASTM Method		AASHTO	ASTM	AASHTO	ASTM
T152	C231	Air content (%)	0.28	0.28	0.8	0.8
T121	C138	Unit weight (lb/ft^3)	*	0.82	*	2.31
T97	C 78	Flexural Strength	*	*	*	*
-	C496	Tensile Strength	-	*	-	*
-	C39	Comp. Strength	-	*	-	*
ITM 403	-	W/C Ratio	*	-	*	-
ITM 404	-	Thickness	*	-	*	-

* Not determined

Table 17. Allowable variation of test results, multi-laboratory precision.

Designations		Tested Parameter (Unit for (1s))	Multi-laboratory Precision			
			Standard deviations (1s) or (1s%)		Acceptable range of two results (d2s) or (d2s%)	
AASHTO/ ITM Method	ASTM Method		AASHTO	ASTM	AASHTO	ASTM
T84	C 128	Fine aggr. G_{sb}	0.023	0.023	0.066	0.066
		SSD G_{sb}	0.020	0.020	0.056	0.056
		G_{sa}	0.020	0.020	0.056	0.056
		Water abs. (%)	0.23	-	0.66	-
T85	C 127	Coarse aggr. G_{sb}	0.013	0.013	0.038	0.038
		SSD G_{sb}	0.011	0.011	0.032	0.032
		G_{sa}	0.011	0.011	0.032	0.032
		Water abs. (%)	0.145	-	0.41	-
T166	D 2726	G_{mb}	*	0.0269[b] 0.0150[c]	*	0.076[b] 0.042[c]
T275	D 1188	G_{mb}	*	0.034	*	0.095
T209	D 2041	G_{mm}	0.0064	0.0160	0.019	0.044
T209 Supplem.	-	G_{mm}	0.0193	0.0193	0.055	0.055
T308/ITM 586	-	P_b (%)	0.06	-	*	-
T152	C231	Air content (%)	*	*	*	*
T121	C138	Unit weight (lb/ft^3)	*	*	*	*
T97	C 78	Flexural Strength	*	7.0% [a]	*	19.0% [a]
-	C496	Tensile Strength	-	*	-	*
-	C39	Comp. Strength	-	*	-	*
ITM 403	-	W/C Ratio	*	-	*	-
ITM 404	-	Thickness	*	-	*	-

* Not determined, a) Coefficient of variation, b) Old specification (2000), c) New specification limit for 12.5-mm and 19.0-mm NMAS mixtures (2004)

For some properties such as bulk specific gravity G_{mb} of the asphalt mixture, the AASHTO method does not give the allowable one-signal limit. Therefore, an applicable ASTM limit or some other suitable precision statement must be used in the analysis, although testing has been done using the AASHTO testing procedure. This is further discussed in the next section. For the plastic air content, AASHTO T152 the multi-operator precision (standard deviation) has been established to present the (1s) and (d2s) limits.

4.4 Precision Development for Calculated Volumetric Quantities

The goal of the research is to assess the variability of the test methods related to the QC/QA acceptance testing. For the HMA, some of the parameters in the volumetric acceptance program are calculated quantities based on the measured test data. The calculated quantities include the air voids content of the gyratory compacted pills (V_a), Voids in Mineral Aggregate (VMA) measured from the pills, and density of the pavement. These properties are calculated using Equations (12) and (13) and (14):

$$V_a = 100 \times (1 - \frac{G_{mb}}{G_{mm}}) \tag{12}$$

$$VMA = 100 - \left(1 - \frac{G_{mb}(1 - P_b)}{G_{sb}} \right) \tag{13}$$

$$Density = 100 - Va \quad or \quad \frac{G_{mb}}{G_{mm}} x100 \tag{14}$$

where:

G_{mm} = maximum theoretical specific gravity of mixture,

G_{sb} = bulk specific gravity of aggregate,

G_{mb} = bulk specific gravity of compacted mixture, and

P_b = asphalt content.

The ASTM D 4460 standard: *"Calculating Precision Limits Where Values are Calculated from Other Test Methods"* presents three procedures for calculating the standard deviation of a test result on which precision limits are based. The following is an excerpt from the D 4460 standard:

5. Procedure

5.1 The standard deviation on which precision limits for a test result are based can be calculated from the following equations:

$$\sigma_{x \pm y} = \sqrt{\sigma_x^2 + \sigma_y^2} \qquad (1) / (15)$$

where:

$\sigma_{x \pm y}$ *= standard deviation for determining precision limits of a test result for a new standard based on either an addition or subtraction of test results from two other standards,*

σ_x *= standard deviation from the precision statement of one of the standards on which the new standard is based, and*

σ_y *= standard deviation from the precision statement of other standard on which new standard is based.*

The distributions of the test results from the two standards should be independent.

$$\sigma_{xy} = \sqrt{\bar{y}^2 \sigma_x^2 + \bar{x}^2 \sigma_y^2} \qquad \textit{(2)} \,/\, (16)$$

where:

σ_{xy} *= standard deviation for determining precision limits of test results for a new standard based on products of two other test results from two other standards,*

σ_x *= standard deviation from the precision statement of one of the standards on which the new standard is based, and*

$\bar{x}$ *= mean or average value of X variable,*

σ_y *= standard deviation from the precision statement of other standard on which new standard is based, and*

$\bar{y}$ *= mean or average value of Y variable.*

$$\sigma_{x/y} = \sqrt{\frac{\bar{y}^2 \sigma_x^2 + \bar{x}^2 \sigma_y^2}{\bar{y}^4}} \qquad \textit{(3)} \,/\, (17)$$

where:

$\sigma_{x/y}$ *= standard deviation for determining precision limits of test results for a new standard based on the quotient of two other test results from two other standards.*

4.4.1 Air Voids Content and Density

For the air voids content the allowable variation can be estimated by the precision and bias calculation method presented in the ASTM D 3203 standard: *"Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures"*, which is based on the Equation (3) given in the ASTM D 4460 standard. The allowed variation for the air void content is computed by combining the variation of the maximum specific gravity G_{mm} and bulk specific gravity G_{mb} tests, as shown in the following example. The average G_{mm} of 2.485 and average G_{mb} of 2.403 which have been used in the calculations present the overall mean (average) values that have been computed from the volumetric acceptance HMA production database discussed later in Chapter 5.

<u>EXAMPLE</u>

Bulk Specific Gravity; Avg. = 2.403, St. dv = 0.0124 (ASTM D 2726-2000)

Theoretical Maximum Specific Gravity; Avg. = 2.485, St. dv = 0.008 (ASTM D2041)

$$\sigma_{x/y} = \sqrt{\frac{(2.485)^2(0.0124)^2 + (2.403)^2(0.008)^2}{(2.485)^2}}$$

This value is in terms of decimal ratio; therefore it should be multiplied by 100 to convert it into percentage. Therefore:

$$\sigma_{x/y} = 0.0059(100) = 0.59\%$$

4.4.2 Voids in Mineral Aggregate (VMA)

For the VMA, the allowable variation is not defined by the AASHTO or ASTM. However, the ASTM D 4460 standard enables the development of a standard deviation on which precision limits can be based for the VMA by combining Equations (2) and (3). The calculation of VMA is based on the ratio of the aggregate bulk specific gravities which is similar to the calculation of the air void content, see Equations (13) and (12). The numerator in Equation (13) computes the specific gravity of aggregate with inter-particle pores filled with air, and the denominator is the bulk specific gravity of the aggregate with intra-particle pores filled with air. The specific gravity of aggregate with inter-particle pores filled with air is computed by excluding the binder portion from the bulk specific gravity of compacted mix by multiplying the G_{mb} with $(1\text{-}P_b)$ where binder content P_b is expressed as a decimal number. Equation (2/16) can be used to estimate the combined variation of these two tests.

Then the variation for the quotient of the two specific gravities can be obtained from Equation (3/17) as follows. Again, the average P_b of 5.3% and average G_{sb} of 2.643 which have been used in the calculations present the overall mean (average) values that have been computed from the volumetric acceptance HMA production database discussed later in Chapter 5. Now the example uses AASTO test method limits. However, because AASHTO T166 does not have precision limits, a limit from the ASTM D2726 method is used in the calculations.

<u>EXAMPLE</u>

Binder content; Avg. = 0.053, St.dv = 0.0004 (both in decimal numbers) (AASHTO T308)
Bulk Specific Gravity; Avg. = 2.403, St. dv = 0.0124 (ASTM D2726-2000)
Aggregate Bulk Specific Gravity; Avg: 2.643, St.dv = 0.01 (average of AASHTO T84 and T85)

$$\sigma_{xy} = \sqrt{(0.947)^2 (0.0124)^2 + (2.403)^2 (0.0004)^2} = 0.0118$$

where 0.947 = (1-0.053).

$$\sigma_{x/y} = \sqrt{\frac{(2.643)^2 (0.0118)^2 + (0.947 * 2.403)^2 (0.01)^2}{(2.643)^2}}$$

This value is in terms of decimal ratio; therefore it should be multiplied by 100 to convert it into percentage. Therefore:

$$\sigma_{x/y} = 0.0055(100) = 0.55\%$$

4.4.3 Precision Limits for Calculated Volumetric Quantities for HMA

The calculated allowable standard deviations for the air voids content and VMA are shown in Table 18 for the single-operator and multi-laboratory precision. Both AASHTO and ASTM precision statements given in Table 15 and Table 17 have been used in the limit calculations. It is important to note that the ASTM D2726 method has a new considerably tighter precision statement compared to the earlier versions of the specification. In addition, the new precision statement is given separately for the 12.5-mm and 19.0-mm nominal maximum aggregate size mixtures being 0.008 and 0.013, respectively. The calculation examples presented above used the old precision statements.

There are many different ways to estimate the precision statement for the calculated volumetric quantities which are of interest here. One way is to calculate one limit for the ASTM test methods and another limit for the AASHTO test methods. However, some precision statements required in the calculations do not exist such as the T166 limit for mixture bulk specific gravity G_{mb}. Then engineering judgment must be used to decide how the missing precision statement is estimated.

Table 18 shows the calculated limits for the air voids content/density obtained from the ASTM D2041 and ASTM D2726 precision statements for both the old (0.59) and new (0.45 for 12.mm and 0.61 for 19.0mm) version of the standard. For the paraffin coated specimens (1.17) the limit is calculated using ASTM D1188 precision statement. These limits are applicable for both the SGC pill air void content and in-place density.

Table 18 also gives the calculated AASHTO limit for the air voids content/density for the paraffin coated specimen (0.32) when T275 is used to obtain the (1s) limit for the G_{mb}. Table 15 gives the (d2s) limit if 0.02 which was divided by 2.8 (see Table 1) to obtain (1s) limit of 0.007.

Next a combined AASHTO/ASTM limit were calculated by replacing the ASTM D2041 test with the AASHTO T209 for the G_{mm}. The ASTM limits were used for the G_{mb} because there is no precision statement for the AASHTO T166 test. The combined limits (0.52, 0.36, and 0.55) are smaller than the ASTM limits because of a tighter control for the G_{mm} test.

The VMA limits were calculated using only AASHTO T308 test for the binder content. First, the old ASTM D2726-2000 test limit and then the new ASTM D2726 limits were used to obtain the VMA (1s) limits of 0.55, 0.44, and 0.57. Both the AASHTO and ASTM have the same precision statements for the aggregate bulk specific gravity G_{sb}. The last calculation was done for the AASHTO T275 method of paraffin coated specimens which yielded a (1s) limit of 0.41.

An adjusted limit for the VMA was also calculated that takes in account the fact that a constant aggregate bulk specific gravity, G_{sb} is used. It is very often the case in the HMA contracts where G_{sb} obtained form the JMF is used instead of measuring the G_{sb} during production.

Table 18 shows that there are large differences in the allowed testing variation limit depending what method is used to estimate them. It is also clear that the new ASTM D2726 limit is tightening the allowed (1s) variation for both the air voids content, in-place density, and VMA, which makes the ASTM and AASHTO limits more closer to each other.

Table 18. Allowable variation for calculated volumetric quantities for HMA.

Agency	**Test Methods Used in the Limit Calculations**	**Calculated Quantity**	**Single-operator (1s)**	**Multi-laboratory (1s)**
ASTM	D2041 / D2726-2000	Air Voids/Density	0.59	1.25
ASTM	D2041 / D2726-2004 12.5mm	Air Voids/Density	0.45	0.90
ASTM	D2041 / D2726-2004 19.0mm	Air Voids/Density	0.61	
ASTM	D2041 / D1188 (Paraffin)	Air Voids/Density	1.17	1.50
AASHTO	T209 / T275 (Paraffin)	Air Voids/Density	0.32	-
AASHTO/ASTM	T209 / D2726-2000	Air Voids/Density	0.52	1.11
AASHTO/ASTM	T209 / D2726-2004 12.5mm	Air Voids/Density	0.36	0.65
AASHTO/ASTM	T209 / D2726-2004 19.0mm	Air Voids/Density	0.55	0.65
AASHTO/ASTM	T308 / D2726-2000 /T84/T85	Pill VMA	0.55 / 0.45[a]	1.13 / 0.97[a]
AASHTO/ASTM	T308 /D2726-2004 /T84/T85 12.5mm	Pill VMA	0.44 / 0.29[a]	0.80 / 0.54[a]
AASHTO/ASTM	T308 /D2726-2004 /T84/T85 19.0mm	Pill VMA	0.57 / 0.47[a]	0.80 / 0.54[a]
AASHTO	T308 /T275 /T84/T85 (Paraffin)	Pill VMA	0.41 / 0.25[a]	-

a) Adjusted VMA limit for constant G_{sb}

5 ANALYSIS OF EXISTING HMA DATA TO QUANTIFY VARIABILITY

Three sources of existing INDOT test data were analyzed statistically. The data provided by INDOT personnel in various formats included: INDOT volumetric acceptance HMA production data designated as data source I, INDOT Ignition study data designated as data source II, and INDOT Inter-laboratory study data designated as data source III. The data from the first data source was used in the QA acceptance process while the other two sets of data were used in the internal quality control of testing by INDOT. All of these data sets were analyzed to assess the variation associated with the testing of the HMA properties defined in the scope of the research. The major data source, though, was the volumetric acceptance data that included the HMA production testing.

5.1 Analysis of Data Source I: INDOT Volumetric Acceptance Production Data

5.1.1 A Description of Data Structure

The INDOT volumetric acceptance production data included a total of 18 HMA projects constructed between 2001 and 2002. Each project included various mixtures such as surface or base mixtures, which were identified by the different Job Mix Formulas (JMF). The nominal maximum aggregate size (NMAS) of the mixtures varied between 9.5, 12.5, 19.0, and 25 mm.

The database included state QA acceptance test results and contractor's quality control QC test results. Approximately 80% of the data were plate samples taken behind the paver either by state or contractor. The contactor also took QC samples from the trucks in the asphalt plant. Pavement cores are also included in the database.

The production database included three types of tests, original tests (X), which were either state acceptance tests or contractor's QC tests, retests of the original material (Y), and backup samples (Z). Only the bulk specific gravity of the mixture, G_{mb} was obtained from replicate measurements, while other properties were obtained testing one sample per sublot. Table 19 summarizes the data structure in the database.

Table 19. Summary of Data Structure.

Number	Variable Name	No of Observations
1	Contact #	18
2	Contractor #	10
3	JMF#	118
4	Nominal Maximum Particle Size (NMPS)	4 (9.2, 12.5, 19,25)
5	Agency	2 (State, contractor)
6	Location	2 (Road, Truck)
7	Test Type	3 (X,Y,Z)
8	Lot	
9	Sublot	
10	Test Method	See Table 18
11	Samples	n = 4209

Figure 2 illustrates the INDOT acceptance sampling process from sublots based on the ITM 802 (Random Sampling) and ITM 580 (Sampling HMA). A detailed description of the sampling locations and process is given in Chapter 3. Two sets of acceptance (X) plate samples were taken behind the paver by the state, and another two backup samples (Z) were taken for the appeal process. Both original and backup plate samples (X, Z) were quartered to obtain two replicate gyratory compacted pills (Pill-1 & Pill-2) for testing. Contractor's plate samples were taken from the same sublot as the state samples, but not necessarily near the state's plate samples. The state takes (X) original samples at random locations in a sublot, which is also where backups are sampled (Z), however the replicates are sampled at different random locations within the sublot.

Cores were obtained from two random locations selected by the Engineer within each sublot. Therefore, the two cores are not true replicates as is pointed out later on in the data analysis.

Table 20 summarizes test methods and tested parameters given in the database. The target value for the air void content of the compacted mixture measured from the gyratory compacted (SGC) pills was 4% according to the Superpave volumetric mixture design criteria. The target for the in-situ density was 94% of the theoretical maximum specific gravity (MSG), G_{mm}. The database had the target values for the VMA but not for the binder content of the mixture.

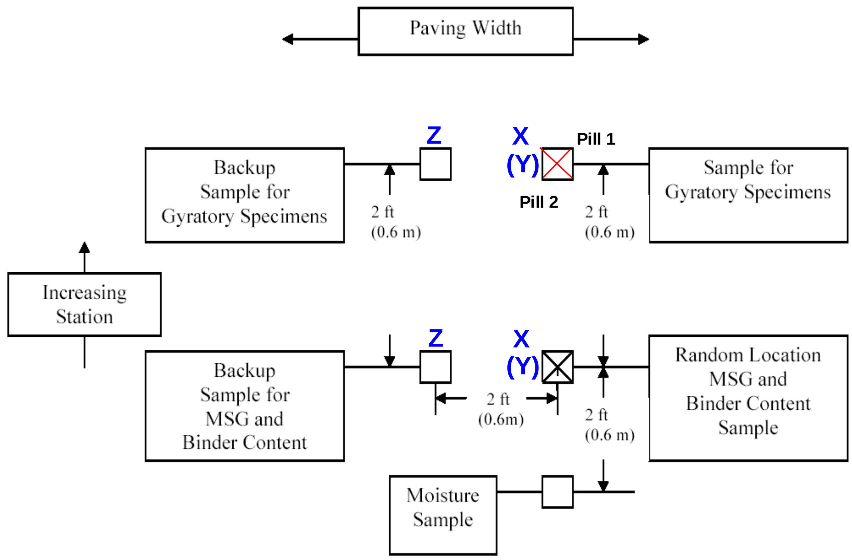

Figure 2. INDOT HMA Plate Sampling, (ITM 580).

Table 20. Test methods and sampling in the database.

Test Method	Parameter	Target value	Notes	Sampling
AASHTO T209	G_{mm}	Variable	From loose mixture	X, Y,Z
ITM 586	P_b (%)	Variable	Target was not given	X, Z*
AASHTO T166	G_{mb}	No target	From SGC pills and cores	X,Y,Z**
AASHTO PP28	V_a (%)	4%	For SGC pills	X,Y,Z
AASHTO PP28	VMA (%)	Variable	For SGC pills	X,Y,Z
AASHTO T275	Density (%)	94%	of MSG for cores	X,Y,Z
AASHTO T166	Density (%)	94%	of MSG for cores	X,Y,Z

* Destructive testing therefore retesting was not possible, ** Two replicate measurements.

5.1.2 Analysis Approach

Testing variation can cause both bias and precision problems. Sampling errors may not show up in precision analysis but they may produce biased measurements compared to the target values. The major sources of material variation in the production testing were assumed to be: 1) material variation caused by production, 2) material variation caused by sampling errors, and 3) material variation caused by testing. The potential sources of variations and their possible causes in the HMA production are summarized in Table 21.

Table 21. Sources of material variation for the HMA production.

Scours of measured material variation	Possible causes of variation	Designation for analysis	Contractors responsibility
Variation caused by production	Mixing: Aggregates and binder mixed using wrong quantities or using segregated aggregates	Production variation s_P^2	Responsible for minimizing variation
	Lay down: Segregation of the mixture due to hauling (drop from the silos), paver operations (augers etc.) and non-uniform compaction of the mat		
Variation caused by sampling errors	Sample splitting: Splitting can produce segregated sample, which will give erroneous test results (see truck sample)	Sampling variation s_s^2	Responsible for preventing errors in the sampling process
	Truck sample: Segregated mixture in the truck bed causes testing variation. If the goal is to asses homogeneity of the mixture (composition), test result need to be discarded and a new non-segregates sample taken.		
	Note: Plate sample: If the goal is to asses laid material variation, taking sample from a segregated spot in the pavement is not considered a sampling error		Responsible for the homogeneity of constructed material
Variation caused by testing	Test method used: Method may intrude inherent material variation, for instance more absorptive aggregates may have more variable test results	Testing Variation s_{TE}^2	Not responsible for testing variation. Testing variation needs to be included while setting the pay factor limits
	Testing: Various random and systematic errors while conducting testing caused by operator, equipment, etc.		
	Inherent material variation: absorptive aggregate or nominal aggregate size might cause some variation beyond the specification (1s) limit		

The components or sources of variation in terms of sample variance can be combined to produce the total material variation in HMA production:

$$s_T^2 = s_P^2 + s_S^2 + \sigma_{TE}^2 \tag{18}$$

where:

s_T^2 = total variance,
s_P^2 = production (mixing, hauling, lay down) variance,
s_S^2 = sampling variance, and
s_{TE}^2 = testing variance

Testing variation (s_{TE}^2), when production and sampling variation is eliminated, includes the variation caused by the testing itself (operator, apparatus, environment, and time) and variation within the tested material other than the production variation. This type of "inherent" material variation may be caused by varying aggregate absorption capacity or nominal aggregate size used in the production and it cannot be easily separated from the testing variation.

Based on the ASTM E177 terminology sampling is a part of the testing variation in the context of testing of homogeneous material. Because the tested samples included the variation coming from the production it was decided to separate the sampling variation from the testing variation if possible.

The major interest in the analysis was the precision, i.e., testing variation for each test method within a JMF because according to the HMA acceptance program: "The mixture properties for each sublot shall meet the requirements for the tolerances from the JMF". Therefore, the pay factors are applied to the sublots as well. It was assumed that the testing was conducted by the contactor or state technicians in the same laboratory (same apparatus and environment), and therefore the single–operator variation was the main interest. The acceptance tolerances given in Table 3 and Table 4 in Chapter 3 must include the single-operator precision indices for testing variation in addition to the acceptable tolerance for the variation in produced material. Therefore, the database was grouped by JMFs to calculate descriptive statistics including mean, variance, standard deviation, coefficient of variation. Once the variation within a JMF was computed the "average" variation was obtained by pooling the variations of each JMF using Equation (3). Figure 3 illustrates the analysis scheme used.

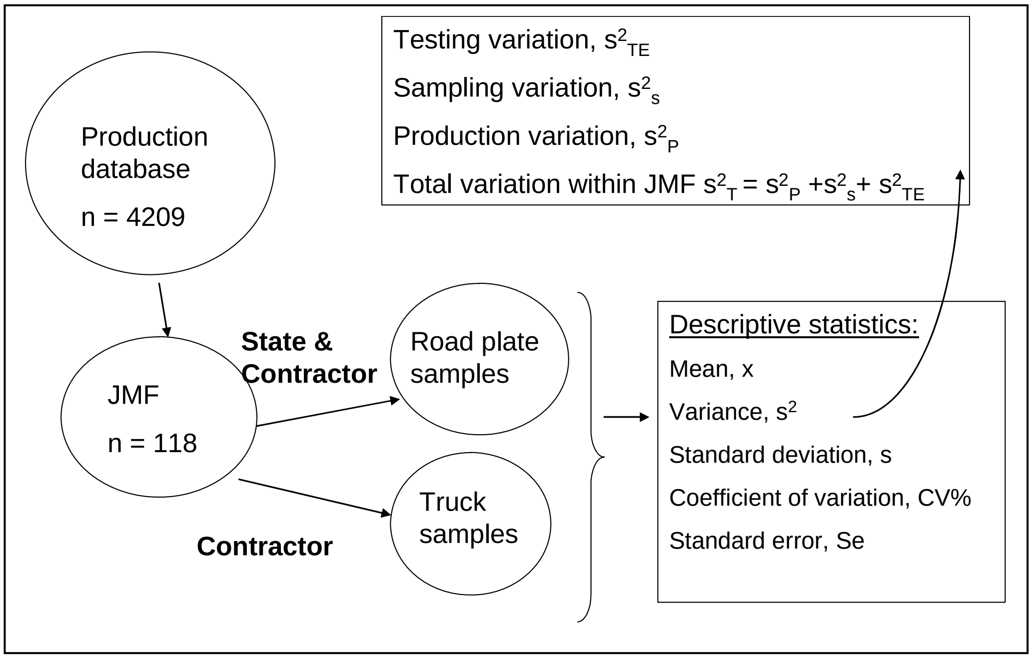

Figure 3. Analysis scheme for the HMA production data.

Test results obtained from the three different types of samples (X, Y, Z) were used in identifying the sources of different material variation identified in Table 21. Statistical data analysis was performed using the following five steps:

1. Total material variance (s_T^2) within a JMF was obtained by grouping the data by JMF and calculating descriptive statistics for the different agencies and sample locations. The pooled variance for all JMFs was computed using Equation (3).
2. Replicate measurements give access to the combined sampling (s_s^2) and testing (s_{TE}^2) variance because the material variation due to production is eliminated. However, only the G_{mb} test was conducted using the replicate SGC pills. The statistics were calculated within the two replicate pills (x_{i1} and x_{i2}) in each sublot within a JMF and then pooled for the "average" variation. This same procedure was

repeated on the two cores obtained from a sublot although they do not represent true replicates because production variation is present. Only the original (X) samples were analyzed.

3. By comparing the original samples (X) and backup samples (Z) in each sublot (x_i and z_i) it was possible to reduce the total material variance (s_T^2) because the production variance (s_P^2) was reduced by the closeness of sampling locations. However, the production and sampling variation still existed in the data. Again, the data was grouped by the JMF and the pooled variance was computed. This analysis was performed to assess testing variation in the test methods that did not have replicate measurements.
4. Finally, the testing variance (s_{TE}^2) was assessed by comparing original testing (X) and retesting (Y) of samples in each sublot (x_i and y_i) within a JMF. In this analysis the observed variation was caused only by the testing because the testing was conducted using the same sample.
5. Inherent material variation that may affect testing variation was assessed by grouping the database by the nominal maximum aggregate size (NMAS). Another possible factor causing inherent material variation is the aggregate water absorption, but this data was not available in the database. This step provides some information of testing variance (s_{TE}^2) due to aggregate size.

It should be noted that the data grouping in the statistical analysis plays a major role in producing desired variation. Table 22 summarizes the above described analysis steps and identifies the sources of variation and bias. Bias here refers to a systematic difference between the target and measured parameter value. For the G_{mb} test, which had the replicate measurements, the average G_{mb} was used in the analysis for Steps 1, 2, 3, 4, and 5. The database was inspected before the analysis and obvious erroneous inputs and outliers were removed.

Table 22. Summary of HMA analysis scheme.

Steps	Samples	Data Grouping See Table 19	Bias			Precision			Variance
			Prod.	Samp.	Test.	Prod.	Samp.	Test.	
1	X_i	3, 5, 6, 7, 10	Y	Y	Y	Y	Y	Y	Total s_T^2
2	X_1, X_2	3, 5, 6, 7, 10	Y	Y	Y	N	Y	Y	Combined $s_s^2 + s_{TE}^2$
3	X_1, Z_1	3, 5, 6, 7, 10	Y	Y	Y	Y*	Y	Y	Reduced Total s_T^2 *
4	X_1, Y_1	3, 5, 6, 7, 10	Y	Y	Y	N	N	Y	Testing s_{TE}^2
5	X_i	3, 4, 5, 6, 7, 10	Y	Y	Y	N	N	Y	Testing s_{TE}^2

* Reduced s_P^2 compared to Step 1.

5.1.3 Analysis Results for Descriptive Statistics

The following tables present the analysis results of the HMA volumetric database employing the analysis steps described above. The analyzed descriptive statistics were:

- Mean, Equation (1),
- Variance, Equation (2),
- Standard deviation, Equation (4), and
- Coefficient of variation (percent), Equation (5).

Due to brevity the tables below present the variation only in the form of standard deviation s (abbreviated as S) omitting the variance to allow comparisons to the precision for each test method given in Table 15 to Table 18 in Chapter 4. The testing standard deviation (S_{TE}) presented in the following tables refers to the within laboratory single-operator (1s) precision.

Step 1

Analysis results for the Step 1 are summarized in Table 23. This variation presents the average HMA production variation within the INDOT JMFs and the QA acceptance tolerances are applied to the data by the state. Overall, the contractor's test results seem to be slightly less variable (standard deviation) than the state test results.

It should be noted that a single test result was used for the G_{mm} and P_b parameters whereas the G_{mb} pills were analyzed using the average of two replicate tests, Pill-1 and Pill-2, obtained from the same plate sample using quartering. Because both samples are from the same plate it can be assumed that the material variation due to production is negligible.

The G_{mb} for cores was also analyzed using averages of two replicate cores, Core-1 and Core-2, which were obtained from the random locations in the sublot. However, in contrast of eliminating the production variation as discussed for compacted pills, the core averages include production variation that is present in the sublot. This is shown in Table 23 where state measured standard deviation for T166 core G_{mb} is 0.0263 which is about 50% larger than the variation for the pill $G_{mb,}$ which is 0.0175.

Step 2

Analysis results for Step 2 are summarized in Table 24. The variation in the test results is reduced compared to Step 1, as expected. However, the difference in the core and pill G_{mb} variation is even larger, cores having three times larger variation than the pills. This is due to production variation present in the core samples, as discussed earlier. The test parameters' averages (means) are very close to the averages given in the previous table indicating that the analysis is sound.

Step 3

Analysis results for Step 3 are summarized in Table 25. Only the state road samples had backup samples. The observed variation is between the variation calculated in Step 1 and 2, as expected. The cores are an exception because they contain sampling and production variation, as discussed in Step 2.

Step 4

Analysis results for Step 4 are summarized in Table 26. Again, only the state road samples were retested. The binder content was not retested due to the destructive nature of testing. This variability is perhaps slightly less than the "true" testing variability (S_{TE}) when compared to the test method one-sigma precision statements. This is to say that there were no testing problems in the first test and retest.

However, it should be noted that although this analysis step gives the testing variation, it might include additional variation which is not accounted for in the allowable limits. This is because the major purpose of the retesting is to verify original test results, which have been determined to be suspicious. Therefore, if the original test results are in large error compared to the retesting, the testing variation will increase exceeding the allowable precision. The allowable testing precision is accounting for random variation caused by operator, machine, environment, and sampling when the proper test procedure is followed. However, large deviations in the test results are usually caused by not conducting testing in accordance to the procedure or malfunctioning of testing equipment.

It should also be noted that for the G_{mm} the retesting may also be affected by the water absorption into the aggregate pores during the original testing, which may increase the testing variability in the retesting.

Step 5

Table 27 shows the testing variation as a function of NMAS for the different mixtures. As the table indicates there are no strong trends suggesting that the NMAS has an effect on testing variation.

Table 23. Statistics within a JMF for truck and road samples (Step 1).

Test Method/ Parameter	Contractor: Truck				Contractor: Road				State: Road			
	Avg	St.Dv	CV%	n	Avg	St.Dv	CV%	n	Avg	St.Dv	CV%	n
T209 G_{mm}	2.475	0.0119	0.444	456	2.475	0.0123	0.462	513	2.492	0.0154	0.550	1115
ITM 586 P_b	5.24	0.22	4.083	455	5.29	0.26	4.724	513	5.31	0.23	4.231	1114
T166 Pill Avg G_{mb}	2.375	0.0154	0.602	455	2.379	0.0171	0.697	511	2.403	0.0175	0.681	1117
PP28 Pill Avg V_a	4.01	0.73	17.510	455	3.86	0.82	20.805	511	3.60	0.93	24.956	1116
PP28 P-Avg VMA	14.53	0.5646	3.626	454	14.18	0.6068	4.171	511	14.06	0.6194	4.172	1113
T166 Core G_{mb}					2.363	0.0285	1.090	33	2.299	0.0263	1.081	776
T166 Core Density					92.48	1.12	1.139	28	92.42	1.52	1.169	755
T275 Core G_{mb}					2.305	0.0320	1.394	25	2.281	0.0271	1.066	189
T275 Core Density					92.97	1.50	1.274	25	91.12	1.41	1.117	206

Table 24. Statistics within a JMF for replicates for truck and road samples (Step 2).

Test Method/ Parameter	Contractor: Truck				Contractor: Road				State: Road			
	Avg	St.Dv	CV%	n	Avg	St.Dv	CV%	n	Avg	St.Dv	CV%	n
T166 Pill Avg G_{mb}	2.375	0.0078	0.296	454	2.379	0.0066	0.257	511	2.403	0.0086	0.314	1116
PP28 Pill Avg V_a	4.03	0.32	7.441	454	3.86	0.27	6.626	511	3.60	0.31	7.986	1112
PP28 P-Avg VMA	14.54	0.2834	1.785	453	14.18	0.2417	1.596	511	14.06	0.3108	1.942	1105
T166 Core G_{mb}					2.363	0.0270	1.087	33	2.297	0.0283	1.186	776
T166 Core Density					92.48	1.04	1.077	28	92.25	1.12	1.157	463
T275 Core G_{mb}					2.305	0.0312	1.348	25	2.281	0.0249	0.968	189
T275 Core Density					93.61	1.40	1.505	15	91.08	1.16	1.108	114

Table 25. Statistics within a JMF for original and backup road samples (Step 3).

Parameter	State: Road			
	Avg	St.Dv	CV%	n
T209 G_{mm}	2.482	0.0126	0.444	951
ITM 586 P_b	5.27	0.20	3.562	960
T166 Pill Avg G_{mb}	2.39	0.0092	0.338	980
PP28 Pill Avg V_a	3.62	0.60	15.467	932
PP28 P-Avg VMA	14.01	0.3760	2.404	938
T166 Core G_{mb}	2.294	0.0147	0.507	498
T166 Core Density	92.40	0.72	0.686	229
T275 Core G_{mb}	2.291	0.0226	1.034	122
T275 Core Density	90.93	0.90	1.209	66

Table 26. Statistics within a JMF for original and retested road samples (Step 4).

Parameter	State: Road			
	Avg	St.Dv	CV%	n
T209 G_{mm}	2.485	0.0079	0.258	1043
T166 Pill Avg G_{mb}	2.39	0.0044	0.126	1050
PP28 Pill Avg V_a	3.62	0.36	8.246	1032
T166 Core G_{mb}	2.292	0.0042	0.157	717
T166 Core	92.17	0.35	0.328	375
T275 Core G_{mb}	2.286	0.0022	0.079	170
T275 Core	91.31	0.42	0.369	79

Table 27. The effect of NMAS for inherent material variation (Step 5).

Test Method	Parameter	State, Road			
		St.Dv for different NMAS			
		9.5 mm	12.5 mm	19 mm	25 mm
AASHTO T209	Gmm	0.0088	0.0085	0.0046	0.0089
AASHTO T166	Pill Gmb	0.0041	0.0030	0.0049	0.0057
AASHTO PP28	Pill Va	0.39	0.35	0.28	0.42
AASHTO T166	Core Gmb	0.0047	0.0026	0.0041	0.0046
AASHTO T166	Core Density	0.31	0.34	0.22	0.39
AASHTO T275	Core Gmb	0.0018	0.0025	0.0023	0.0025
AASHTO T166	Core Density	0.37	0.47	0.45	0.51

5.1.4 Summary and Assessment of Testing Precision

To assess the testing variation the pooled standard deviations were compared to the precision statements by the AASHTO and ASTM presented in Table 15 and Table 17 in Chapter 4. For the testing conducted according to the AASHTO T166 and T275 test methods, the precision statement obtained from the AASHTO T275 was used for both of them because T166 does not have a precision statement.

The justification of doing this is shown in Figure 4 which compares the measured G_{mb} values to the latest ASTM D2726-2004 (1s) limits of 0.008 for the 12.5mm NMAS mixture and 0.13 for the 19.0-mm NMAS mixture with the AASHTO T275 limit of 0.007. The figure shows that all measured testing variation was well below the AASHTO T275 limit and there does not seem to be any noticeable increase in testing variation as the NMAS is increasing. Therefore, the use of T275 limit of 0.007 for mixture bulk specific gravity testing variation is justified, although it presents the tightest of limits allowed for the testing variation.

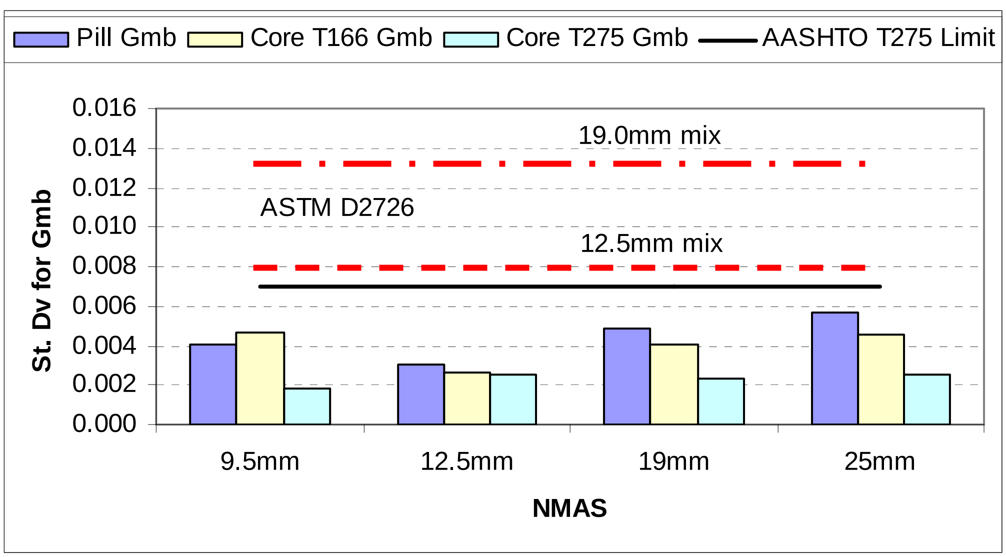

Figure 4. Summary of the G_{mb} Variation as Function of NMAS.

The limits for the calculated quantities, air voids content, VMA, and density are shown in Table 18 in Chapter 4. The adjusted limit for the VMA was selected because INDOT database did not have measured aggregate bulk specific gravity values and a constant G_{sb} obtained from the JMF was used to calculate VMA. Then, the selected (1s) limit for the air voids content and in-place density is 0.32 and the (1s) limit for the VMA is 0.25.

Table 28 and Table 29 summarize the analysis results for the variability (standard deviation) presented in Table 23 to Table 27 for the studied test methods. Table 28 shows the contractor variation in the truck and road and Table 29 shows the state road samples which are used for acceptance. Standard deviation (S_T) presents the total variance (s_T^2), and combined sampling and testing standard deviation designated as (S_S+S_{TE}) presents the combined sampling and testing variance ($s_s^2 + s_{TE}^2$). Table 28 and Table 29 show the allowable testing variation one-sigma (1s) limit for each test method, as discussed above.

Table 28. Summary of material variation for each test method for contractor.

Test Method	Parameter	Contractor					
		Truck		Road		Limit	
		s_T (Step 1)	s_S+s_{TE} (Step 2)	s_T (Step 1)	s_S+s_{TE} (Step 2)	(1s)	Adj. (1s)
AASHTO T209	Gmm	0.0119		0.0123		0.0040	
ITM 586	Pb	0.219		0.26		0.04	
AASHTO T166	Pill Gmb	0.0154	0.0078	0.0171	0.0066	0.007	
AASHTO PP28	Pill Va	0.729	0.318	0.822	0.270	0.32	
AASHTO PP28	Pill VMA	0.564	0.283	0.607	0.242	0.41	0.25
AASHTO T166	Core Gmb			0.0285	0.0270	0.007	
AASHTO T166	Core Density			1.12	1.04[a]	0.32	
AASHTO T275	Core Gmb			0.0320	0.0312	0.007	
AASHTO T275	Core Density			1.50	1.394[a]	0.32	

a) Includes some production variation

Table 29. Summary of material variation for state road samples.

Test Method	Parameter	Road				Limit	
		s_T (Step 1)	s_T^* (Step 3)	s_S+s_{TE} (Step 2)	s_{TE} (Step 4)	(1s)	Adj. (1s)
AASHTO T209	Gmm	0.0154	0.0126		0.0079	0.0040	
ITM 586	Pb	0.23	0.20			0.04	
AASHTO T166	Pill Gmb	0.0175	0.0092	0.0086	0.0044	0.007	
AASHTO PP28	Pill Va	0.93	0.60	0.31	0.36	0.32	
AASHTO PP28	Pill VMA	0.6194	0.3760	0.3108		0.41	0.25
AASHTO T166	Core Gmb	0.0263	0.0147	0.0283	0.0042	0.007	
AASHTO T166	Core Density	1.52	0.72	1.12[a]	0.35	0.32	
AASHTO T275	Core Gmb	0.0271	0.0226	0.0249	0.0022	0.007	
AASHTO T275	Core Density	1.41	0.90	1.16[a]	0.42	0.32	

a) Includes some production variation

Figure 5 to Figure 13 compare observed variation between contractor truck and road samples and state road samples. Material variation included in the figures is comprised of a) total variation including production, sampling and testing variation (Step 1 analysis); b) reduced production variation (Step 3 analysis): c) material variation caused by sampling and testing (Step 2 analysis); and d) material variation caused by testing (Step 4). In Step 3 the production variation is reduced by the closeness of road plate samples that were compared.

Figure 5 shows that for maximum specific gravity G_{mm} the acceptance testing variation was not within the (1s) limit of 0.040 indicating that there are problems in executing this test. Half of the total variation (0.0154) consisted of testing variation. Sampling location (truck or plate road sample) did not seem to increase the total variation compared to the precision difference between the state and contractor testing.

For the retested G_{mm} specimens, about 20% of the test results had variation larger than the acceptable range of two test results (d2s) of 0.011. About 11% of the cases the retested G_{mm} value was higher than the original test results, the average difference being 0.022. In about 9% of the cases the retested G_{mm} was lower, the average difference being 0.025. This suggests that some errors associated with the G_{mm} testing are related to how completely the air is removed from the sample (loose mixture) during testing. Air entrapped inside the loose mixture will decrease the obtained maximum specific gravity value of the mix.

Figure 6 shows that for percent binder P_b the acceptance testing variation could not be separated from the production variation. For the binder content, the state plate sample testing had slightly lower variation compared to the contractor plate samples.

Figure 7 shows that for pill bulk specific gravity G_{mb} the testing variation (T166) was below the (1s) limit of 0.007. About 25% of the total variation (0.0175) consisted of testing variation. In addition, the combined sampling and testing variation was only slightly above the testing limit indicating that material sampling has been conducted properly. The state road samples had slightly higher variation than the samples tested by the contractor. This suggests that material sampling from trucks was conducted properly and it did not increase testing variation.

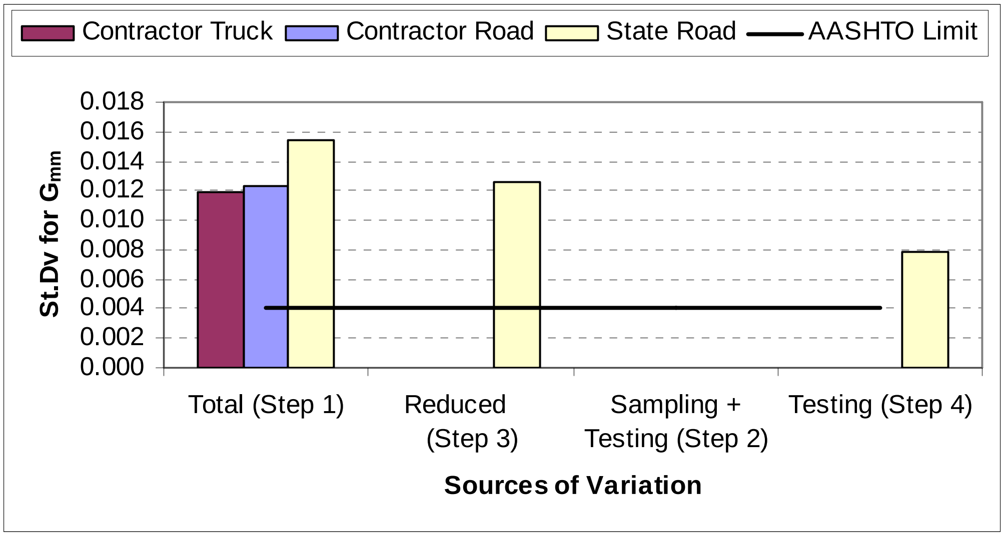

Figure 5. Summary of the G_{mm} Variation.

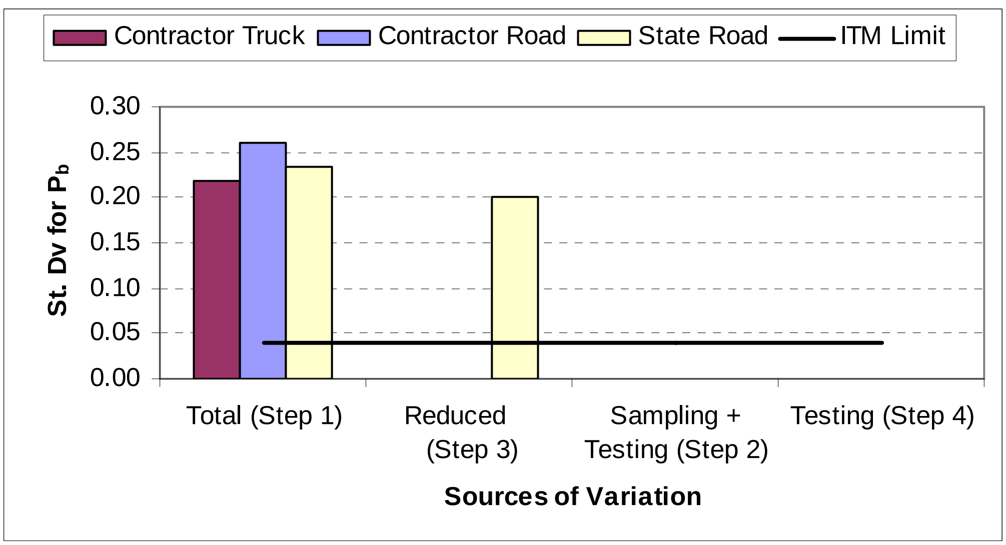

Figure 6. Summary of P_b Variation.

Figure 8 shows that for gyratory pill air void content the testing variation (T 166) was slightly above the (1s) limit of 0.32. About 39% of the total variation (0.93) consisted of testing variation. The combined sampling and testing variation for the pill V_a is less than the testing variation from Step 4. Because the testing variation is assessed using retesting of original samples, the testing errors associated with the original testing may increase the testing variability, as was demonstrated in Figure 5 for the G_{mm} testing.

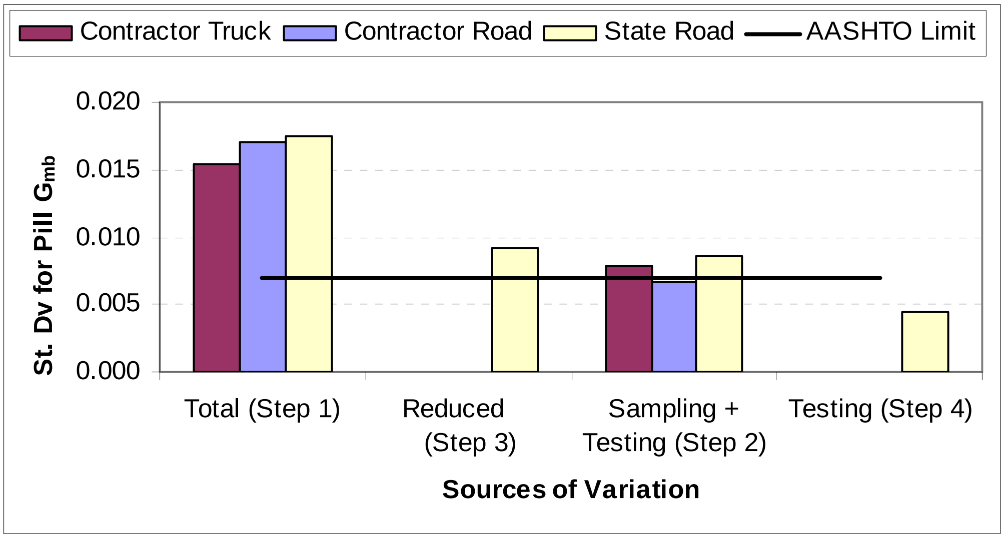

Figure 7. Summary of Pill G_{mb} Variation.

Figure 9 shows that for the pill VMA the combined sampling and testing (S_S+ S_{TE}) variation was at or slightly above the (1s) adjusted limit of 0.25. The combined variability was about 50% of the total variability (0.62). The state road samples had a slightly higher variability than the samples tested by the contractor for the total variability (S_T).

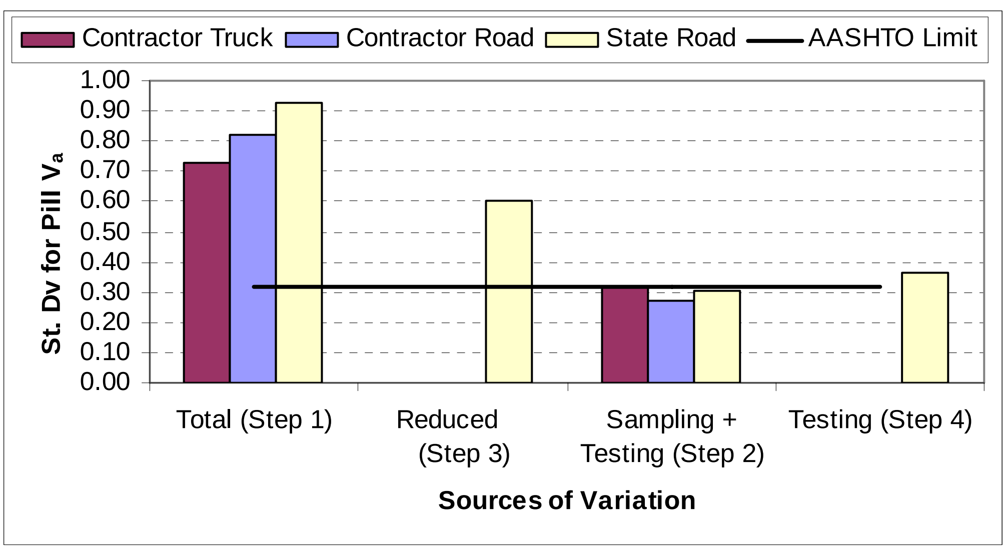

Figure 8. Summary of Pill V_a Variation.

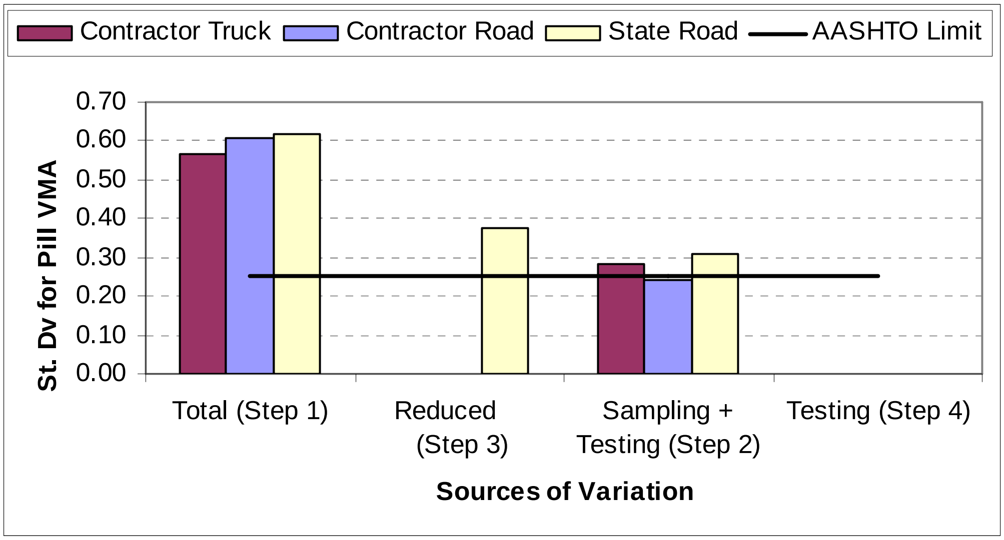

Figure 9. Summary of Pill VMA Variation.

Figure 10 and Figure 11 show that for core G_{mb} and for core density the testing variations (T166) were within the (1s) limit of 0.007 and 0.32. The back-up samples (Step 3) were obtained next to the original samples while the two random cores (Step 4) were obtained further apart. The variation between the original samples and back-up samples is then smaller than between Core-1 and Core-2 in a sublot, as can be expected. The total variation (0.0263 and 1.52) consisted of testing variation up to 23%. Again, the state had higher variation compared to the contractor testing.

Figure 12 and Figure 13 show that for core G_{mb} and for core density the acceptance testing variations for paraffin-coated specimens (T275) were within or slightly above (1s) limits of (0.007) and (0.32). The effect of sampling on the measured material variation, similar to that discussed earlier, can be observed from the figures. The total variation (0.0271 and 1.41) consisted of testing variation up to 30%. The increase in core density testing variation compared to core G_{mb} testing variation contributes to the increase in G_{mm} testing variation. The state had a slightly lower variation as compared to the contractors testing.

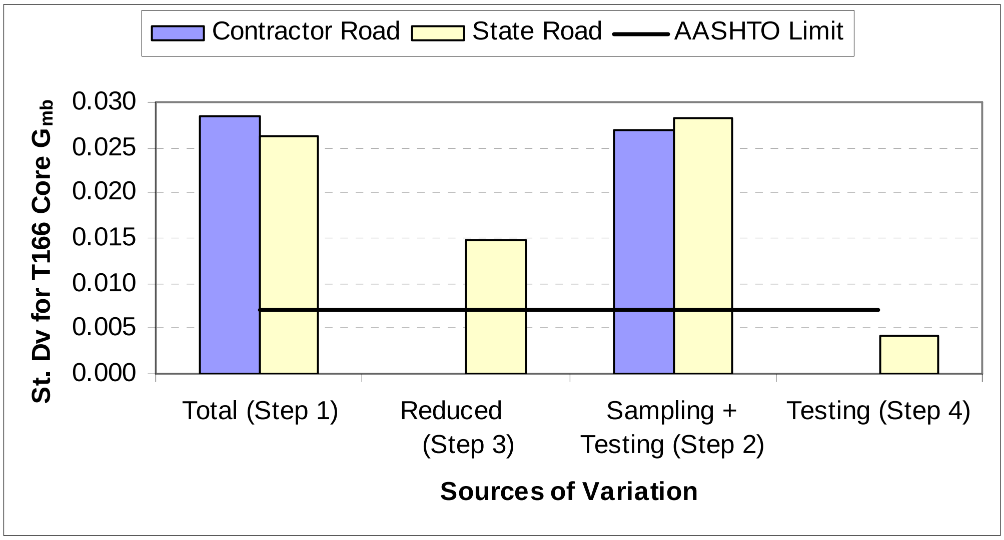

Figure 10. Summary of T166 Core G_{mb} Variation.

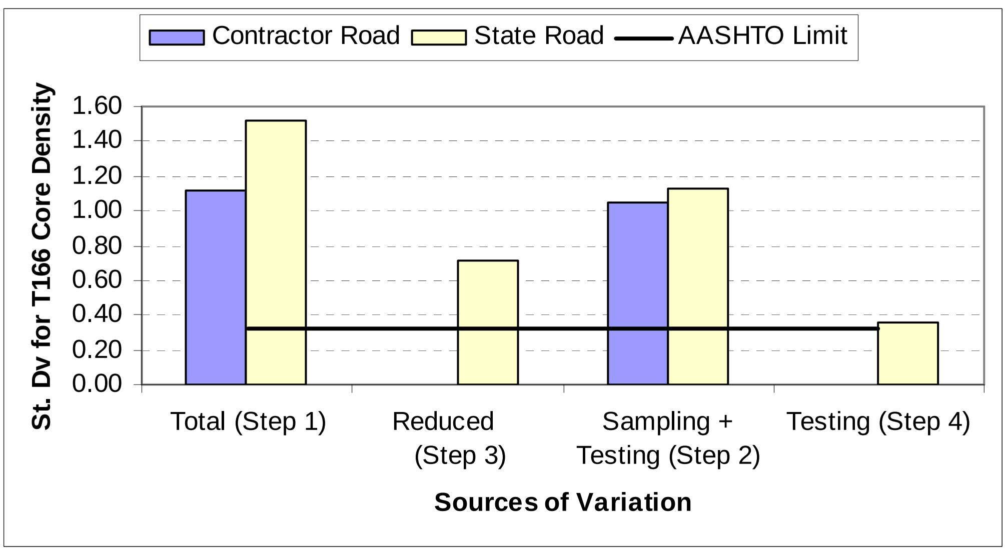

Figure 11. Summary of T166 Core Density Variation.

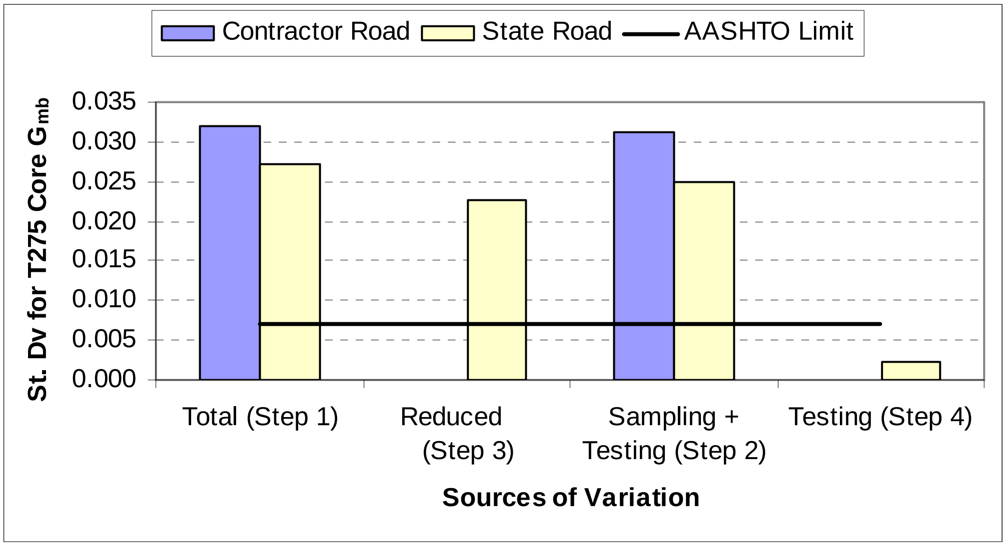

Figure 12. Summary of T275 Core G_{mb} Variation.

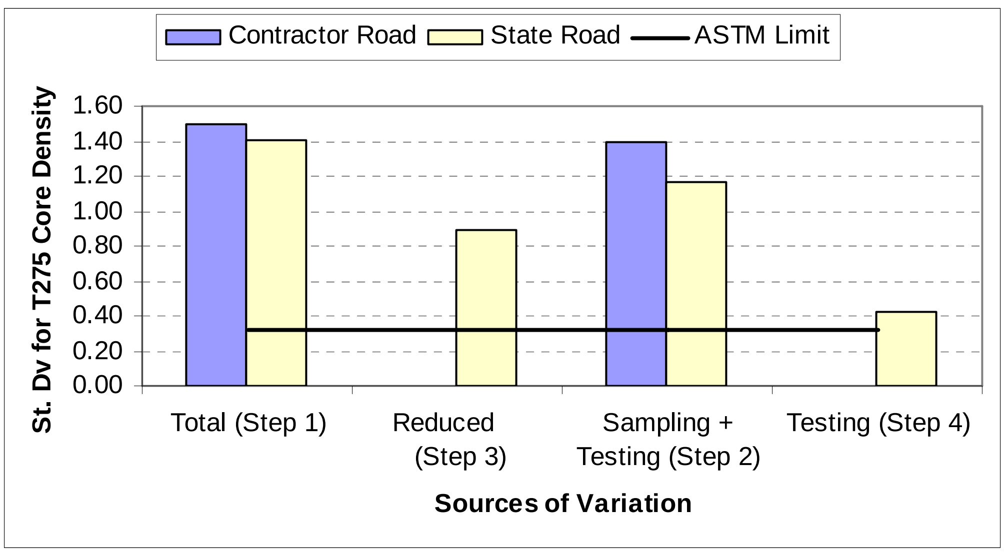

Figure 13. Summary of T275 Core Density Variation.

5.1.5 Summary and Assessment of Bias in Test Results

Table 30 and Table 31 summarize the analysis results for mean (average) values of measured quantities presented in Table 23 to Table 26 for the studied test methods. The bias represents the difference between the measured quantity(ies) and the target value.

Only air voids content, density, and VMA had target values in the database and bias could be assessed.

Table 30. Summary of the mean value for each test method for contractor samples.

Test Method	Parameter	Contractor			
		Truck		Road	
		s_T (Step 1)	s_S+s_{TE} (Step 2)	s_T (Step 1)	s_S+s_{TE} (Step 2)
AASHTO T209	Gmm	2.475		2.475	
ITM 586	Pb	5.24		5.29	
AASHTO T166	Pill Gmb	2.375	2.375	2.379	2.379
AASHTO PP28	Pill Va	4.02	4.03	3.86	3.86
AASHTO PP28	Pill VMA	14.52	14.54	14.18	14.18
AASHTO T166	Core Gmb			2.363	2.363
AASHTO T166	Core Density			92.48	92.48
AASHTO T275	Core Gmb			2.305	2.305
AASHTO T275	Core Density			92.97	93.60

Table 31. Summary of the mean value for state road samples.

Test Method	Parameter	Road			
		s_T (Step 1)	s_T^* (Step 3)	s_S+s_{TE} (Step 2)	s_{TE} (Step 4)
AASHTO T209	Gmm	2.492	2.482		2.485
ITM 586	Pb	5.31	5.27		
AASHTO T166	Pill Gmb	2.403	2.391	2.403	2.395
AASHTO PP28	Pill Va	3.60	3.62	3.60	3.62
AASHTO PP28	Pill VMA	14.06	14.01	14.06	
AASHTO T166	Core Gmb	2.299	2.294	2.297	2.292
AASHTO T166	Core Density	92.42	92.40	92.25	92.17
AASHTO T275	Core Gmb	2.281	2.291	2.281	2.286
AASHTO T275	Core Density	91.12	90.93	91.08	91.31

Figure 14 to Figure 16 compare the observed bias between contractor truck and road sample means, and state road sample means separated by the different analysis steps. Figure 14 shows that there is a systematic trend in the pill VMA measurements indicating decrease in the VMA values while comparing truck and road plate samples. The truck samples are closer to the target values. The target VMA of 14.48 was computed from the INDOT database by averaging all VMA values.

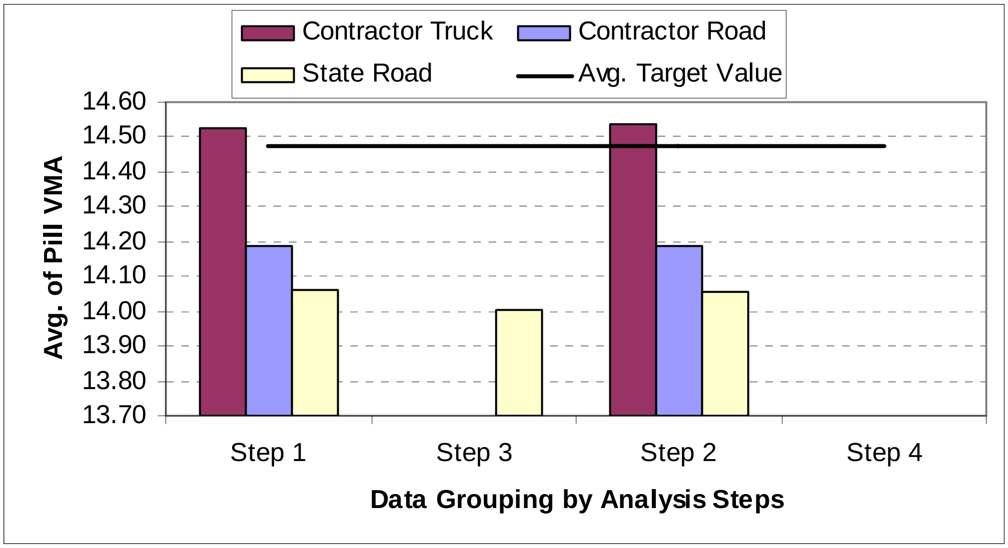

Figure 14. Summary of Pill VMA Means.

In a similar manner, Figure 15 shows that there is a systematic trend in the measured air voids content values compared to the truck and road samples. Again, the truck samples are closest to the target air voids content of 4% of the gyratory compacted pills. As an average, the state road samples deviated 10% of the target air voids content. Contractor road samples are closer to the target values deviating only about 4%.

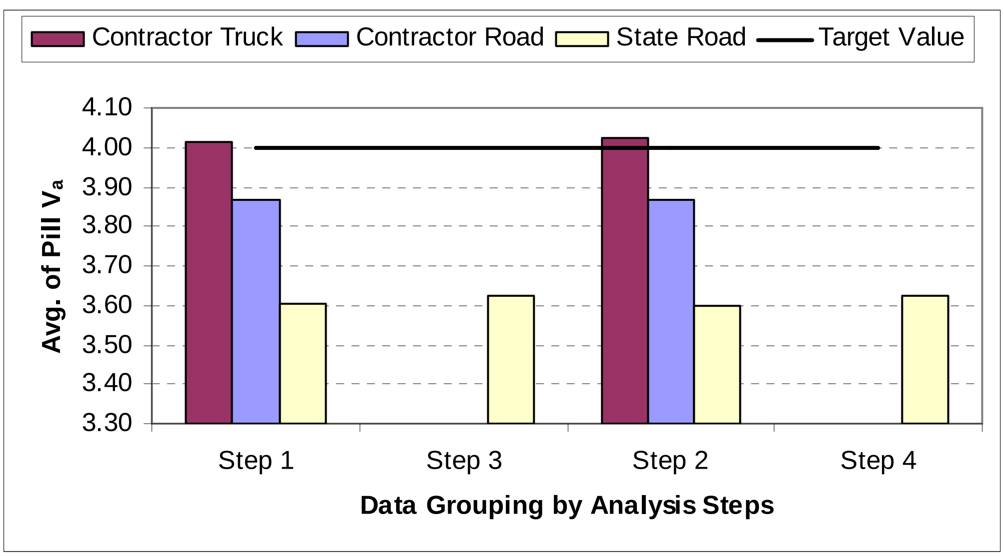

Figure 15. Summary of Pill V_a Means.

Figure 16 shows a systematic trend in the pavement density measurements. Overall, the compacted mix had approximately 7.7% air voids content when the specified target is 6% or 94% of MSG (to obtain 5% bonus) and 92 to 93% of MSG or 7 to 8% air voids content to obtain full pay.

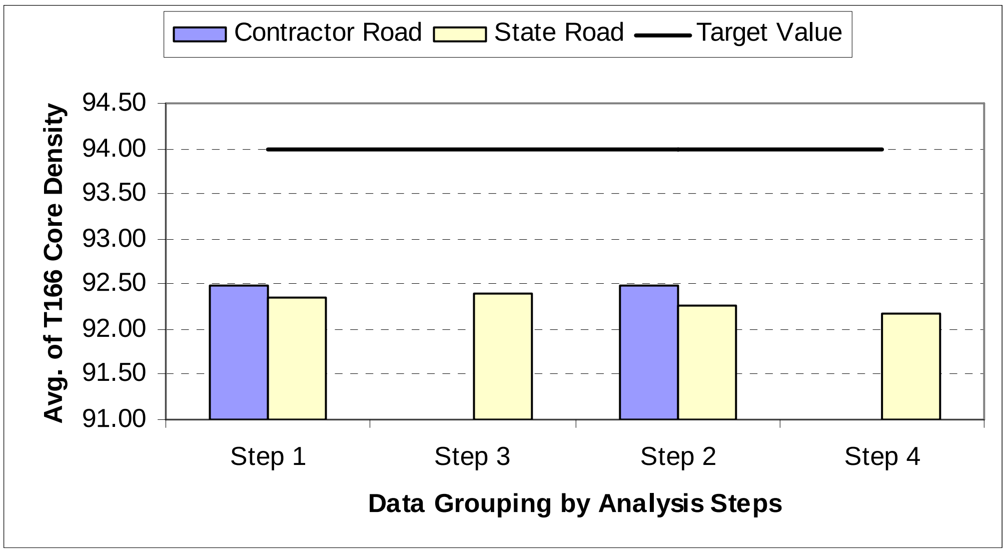

Figure 16. Summary of T166 Core Density Means.

5.1.6 Variability between Contactors

Figure 17 to Figure 21 show the total material variation within a JMF as a function of different contractors. Ten different contractors were listed in the database. Each figure shows the road sampling results recorded by the state.

Overall, only one contractor designated as D stood out from the analysis indicating very poor production control in all test categories. In a similar manner contractors G and H showed poor production control in the pill air voids content and VMA results, while contractor J kept the VMA variation down by having tighter control for the G_{mb} variation in the gyratory compaction.

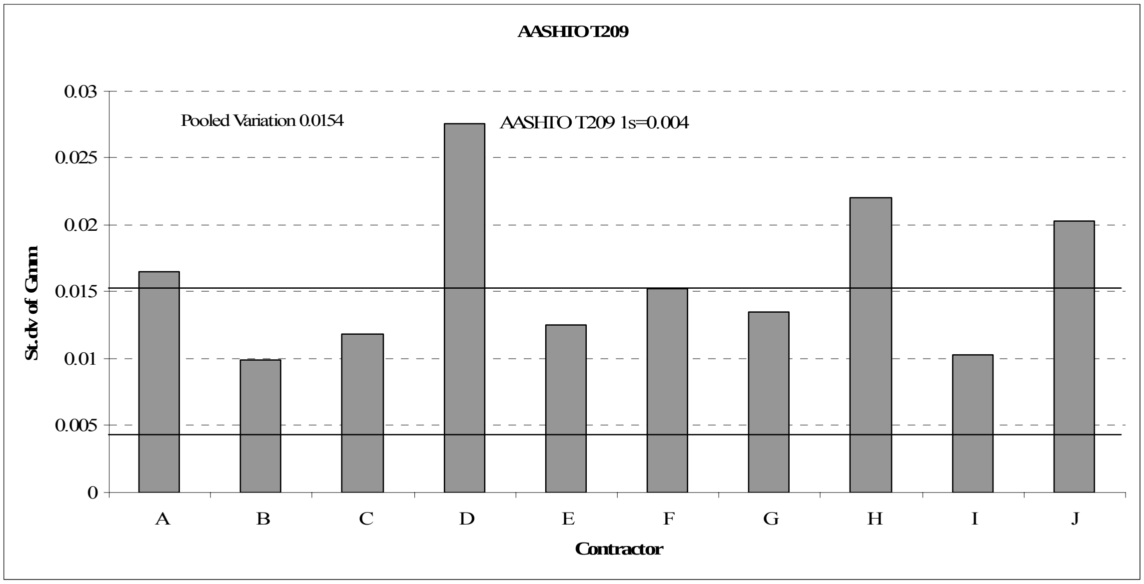

Figure 17. Total variability (S_T) of G_{mm} within a JMF.

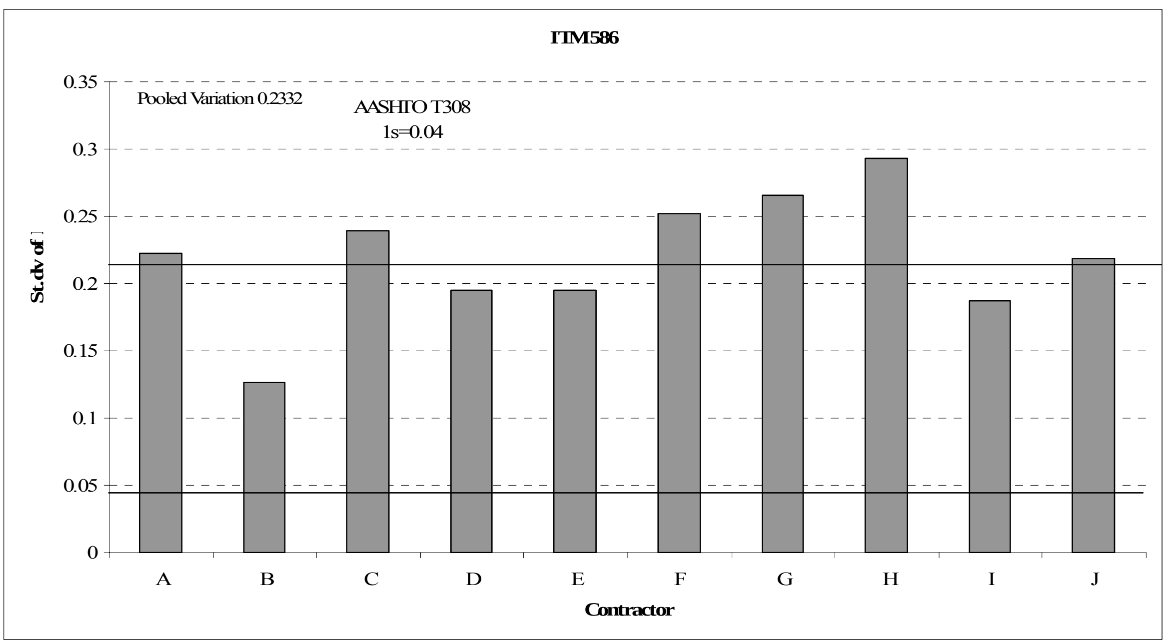

Figure 18. Total variability (S_T) of P_b.

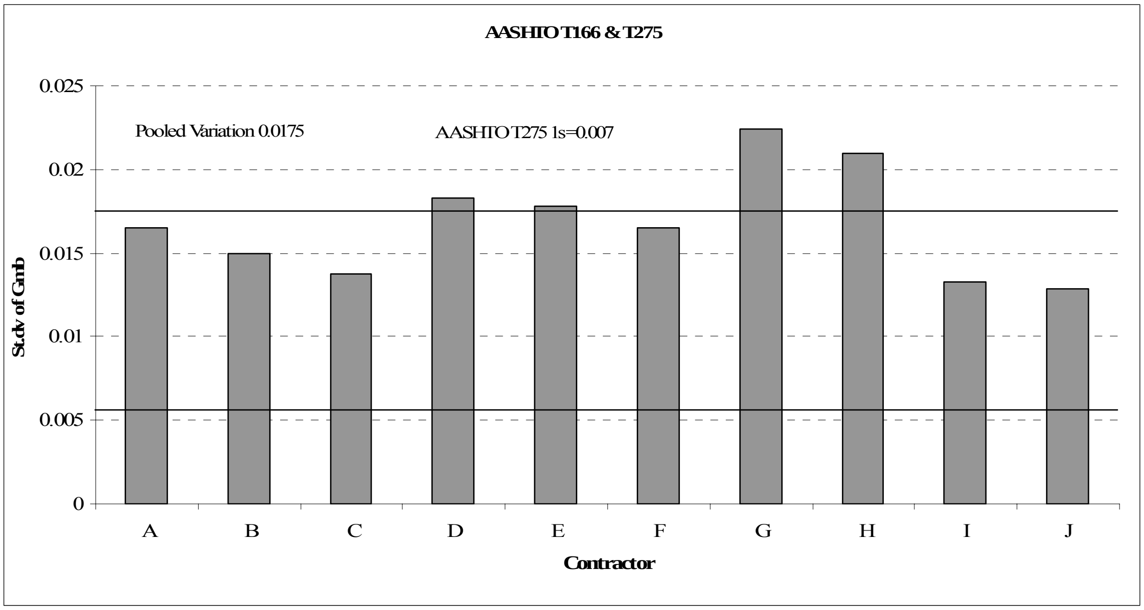

Figure 19. Total variability (S_T) of Pill G_{mb}.

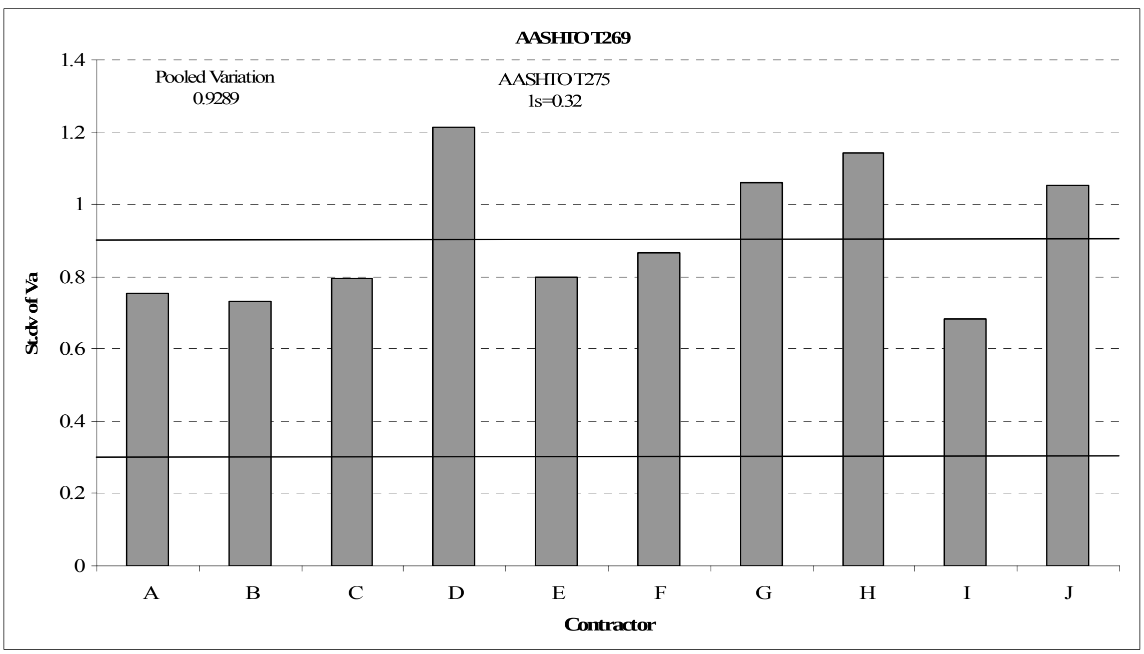

Figure 20. Total variability (S_T) of V_a.

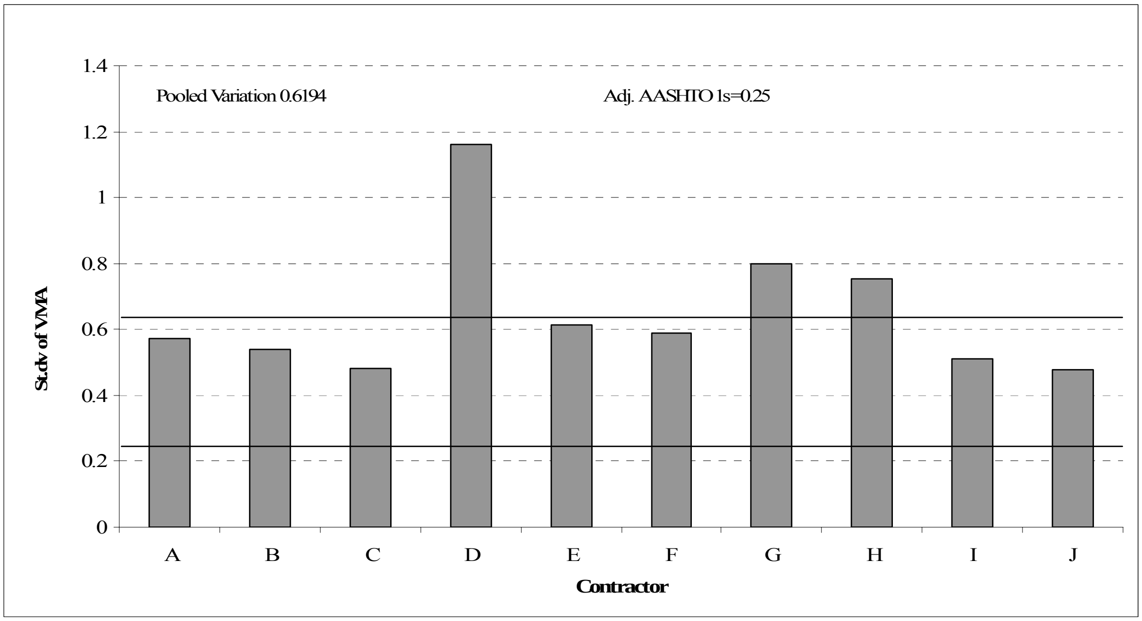

Figure 21. Total variability (S_T) of VMA.

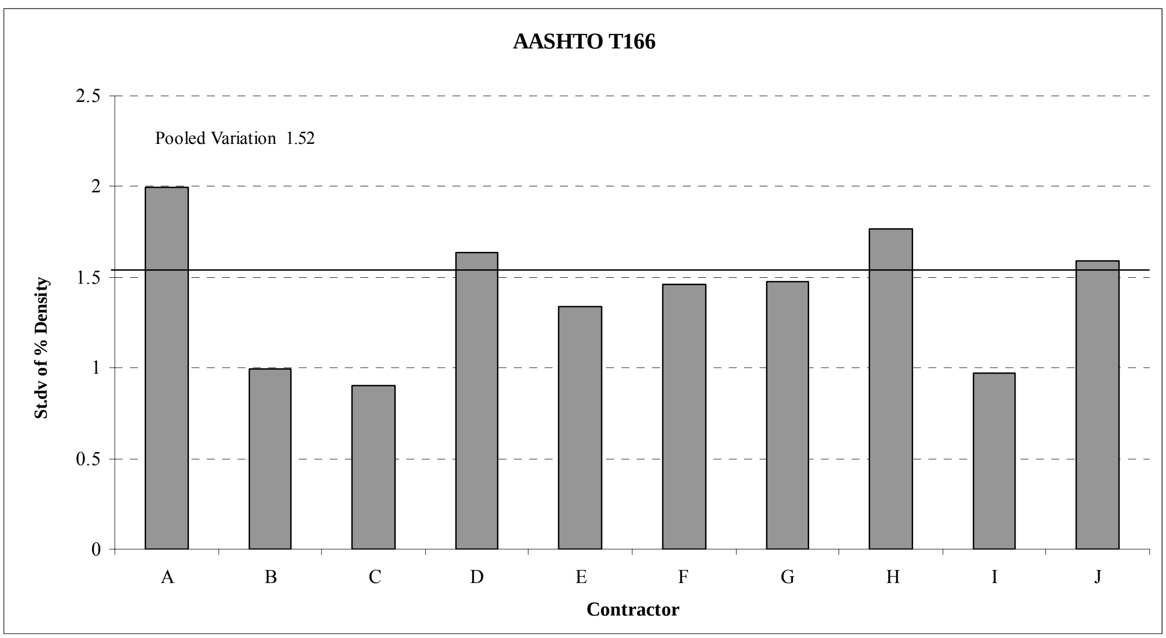

Figure 22. Total variability (S_T) of % In-Place Density.

5.2 Analysis of Data Source II: INDOT Ignition Study Data

5.2.1 A Description of Data Structure

The Ignition Study Data which was performed by the INDOT's Materials and Tests Division consisted of 1082 tests conducted by both contractors and state agencies. The tests were preformed in seven separate phases. Each of the phases differed by the type of coarse aggregate that was used, the rest of the parameters remained the same including the target binder content. For each phase, all samples were prepared with the same aggregate source and same aggregate gradation. The coarse aggregates used in each phase of the testing are outlined in Table 32. The samples were prepared in INDOT central lab, and then sent to different district labs for testing. Each test contained results of a sieve analysis along with a percent binder and test machine. Two test results of the same sample were obtained by a single-operator using a single machine. All binder content tests were performed according to ITM 586. Table 33 outlines the data structure of the ignition study.

Table 32. Summary of Tested Aggregates.

Phase	CA Source #	Source	Aggregate/ Mineral
I	2450	Levy Slag	Blast Furnace Slag
II	2542	Sellersburg Stone	Limestone
III	2521	Rogers Group	Limestone
IV	2135	Hanson Aggregates	Limestone
V	2535	Meshberger Stone	Limestone
VI	2311	Martin Marietta	Limestone
VII	2164	Rogers Group	Crushed Gravel

Table 33. Summary of Data Structure.

Number	**Variable Name**	**No of Observations**
1	Phase	7 data sets
2	District	8
3	Area Lab	41
4	Lab Technician	132
5	Testing Machine Model	6
6	Serial Number	137
7	Samples	N=640

All of the samples where prepared with a 5.0% target for the percent of binder. Each test included two samples, which can be considered replicates. Table 34 outlines the sampling procedures of the study.

Table 34. Test Method and Sampling.

Test Method	Parameter	Target value	Notes	Sampling
ITM 586	P_b (%)	5.0%	Target was given	X**

** Two replicate measurements.

5.2.2 Analysis Approach

The samples for each phase were fabricated at INDOT's central lab. They were then distributed to the different agencies responsible for testing. Therefore there is no (or very little) variation introduced by sample fabrication or sampling and the majority of variation that is present is the material variation caused by the testing of the samples.

As mentioned before, two test results of the same sample were obtained by a single-operator using a single machine. Thus, testing variation was obtained by comparing two replicate test results which produce a single-operator precision. A pooled standard deviation was calculated from these numbers by grouping data by phase, district, area lab, and machine model.

5.2.3 Analysis Results for Descriptive Statistics

The following tables present the analysis results of the HMA binder database employing the analysis steps described above. The analyzed descriptive statistics were:

- Mean, Equation (1),
- Variance, Equation (2),
- Standard deviation, Equation (4), and
- Coefficient of variation (percent), Equation (5).

Due to brevity, Table 35 through Table 39 present the variation only in the form of standard deviation omitting the variance to allow comparisons to the precision for each test method.

Table 35. Average Statistics for Ignition Data by District.

District	n	Avg.	CV (%)	Standard Deviation							
				I	II	III	IV	V	VI	VII	Pooled
Central Test	23	5.34	0.8	0.033	0.074	0.028	0.015	0.066	0.022	0.049	0.050
Contractor	122	5.24	1.6	0.099	0.107	0.082	0.080	0.036	0.075	0.112	0.088
Crawfordsville	62	5.32	1.3	0.075	0.096	0.032	0.039	0.097	0.071	0.053	0.072
Fort Wayne	55	5.27	1.4	0.069	0.031	0.048	0.121	0.089	0.082	0.063	0.079
Greenfield	58	5.28	1.2	0.070	0.049	0.034	0.030	0.048	0.068	0.171	0.080
LaPorte	68	5.25	1.2	0.048	0.051	0.106	0.062	0.051	0.054	0.064	0.065
Seymour	73	5.21	1.3	0.075	0.053	0.031	0.080	0.063	0.066	0.085	0.067
Vincennes	70	5.24	1.0	0.049	0.057	0.023	0.034	0.065	0.027	0.115	0.060

Table 36. Average Statistics for Ignition Data by Phase.

Phase	Avg.	St.Dv	CV (%)	n
I	4.88	0.075	1.5	82
II	5.25	0.078	1.4	73
III	5.03	0.063	1.1	78
IV	5.09	0.069	1.2	79
V	5.61	0.066	1.1	68
VI	5.37	0.065	1.2	79
VII	5.67	0.100	1.6	72

Table 37. Average Statistics for Ignition Data by Contractor Area Labs.

District	Area Lab	n	St. Dv	Avg.
Contractor	A	1	-	5.65
Contractor	B	14	0.141	5.22
Contractor	C	19	0.102	5.22
Contractor	D	17	0.062	5.23
Contractor	E	7	0.071	5.13
Contractor	F	8	0.065	5.16
Contractor	G	3	0.058	4.97
Contractor	H	10	0.103	5.45
Contractor	I	9	0.030	5.12
Contractor	J	6	-	5.23
Contractor	K	14	0.098	5.28
Contractor	L	8	0.035	5.38
Contractor	M	6	-	5.17

Table 38. Average Statistics for Ignition Data by Machine Model.

Machine Model	n	Avg.	Standard Deviation							
			Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Pooled
Other	114	5.29	-	0.130	0.034	0.086	0.068	0.069	0.146	0.071
Series 1087	383	5.24	0.075	0.064	0.073	0.060	0.064	0.064	0.098	0.074
Series 945	31	5.38	0.092	0.135	0.018	0.042	0.069	0.024	0.075	0.085

Table 39. Average Statistics for Ignition Data by State Area Labs.

District	Area Lab	n	St. Dv	Avg.
Central Test	AMRL	5	-	5.37
Central Test	Materials & Tests	18	0.027	5.33
Crawfordsville	Crawfordsville Area	21	0.049	5.38
Crawfordsville	Lafayette	21	0.098	5.34
Crawfordsville	Terre Haute	20	0.061	5.23
Fort Wayne	Brooks Construction	1	-	5.35
Fort Wayne	Fort Wayne Area	13	0.060	5.30
Fort Wayne	Fort Wayne District	14	0.101	5.31
Fort Wayne	Orland	13	0.074	5.23
Fort Wayne	Wabash	13	0.076	5.25
Fort Wayne	Warsaw	1	-	5.01
Greenfield	Greenfield District	7	-	5.39
Greenfield	New Castle	26	0.057	5.32
Greenfield	Tibbs	25	0.099	5.21
LaPorte	Hammond	18	0.070	5.20
LaPorte	LaPorteDistrict	23	0.051	5.29
LaPorte	Logansport	14	0.091	5.29
LaPorte	South Bend	13	0.045	5.20
Seymour	Columbus	14	0.054	5.23
Seymour	Osgood	14	0.039	5.26
Seymour	Sellersburg	31	0.072	5.21
Seymour	Seymour District	14	0.088	5.13
Vincennes	Bloomfield	15	0.056	5.05
Vincennes	Dale	14	0.035	5.30
Vincennes	Evansville	14	0.103	5.30
Vincennes	Vincennes District	22	0.031	5.24
Vincennes	Vincennes Area	5	0.034	5.53

5.2.4 Summary and Assessment of Precision

To assess the testing variation the pooled standard deviations were compared to the precision statements by the AASHTO specifications. Figure 23 shows the variation by testing phase in relation to the AASHTO T308 (1s) limit of 0.04 for a single-operator variation. Figure 24 shows the testing variation by testing agency compared to the (1s) limit. The Vincennes district seems to be closest to the allowed variation limit. Figure 25 displays the variation by the machine that was used to perform the test. The Series 1087 yielded the best results for this study. In Figure 26 the contractors data is compared to the (1s) limit. Contractor I was the only contractor below the (1s) limit for this testing. Figure 27 displays the ignition testing by state area lab. Five out of twenty-two of the state's area labs had a variation that was below the (1s) limit.

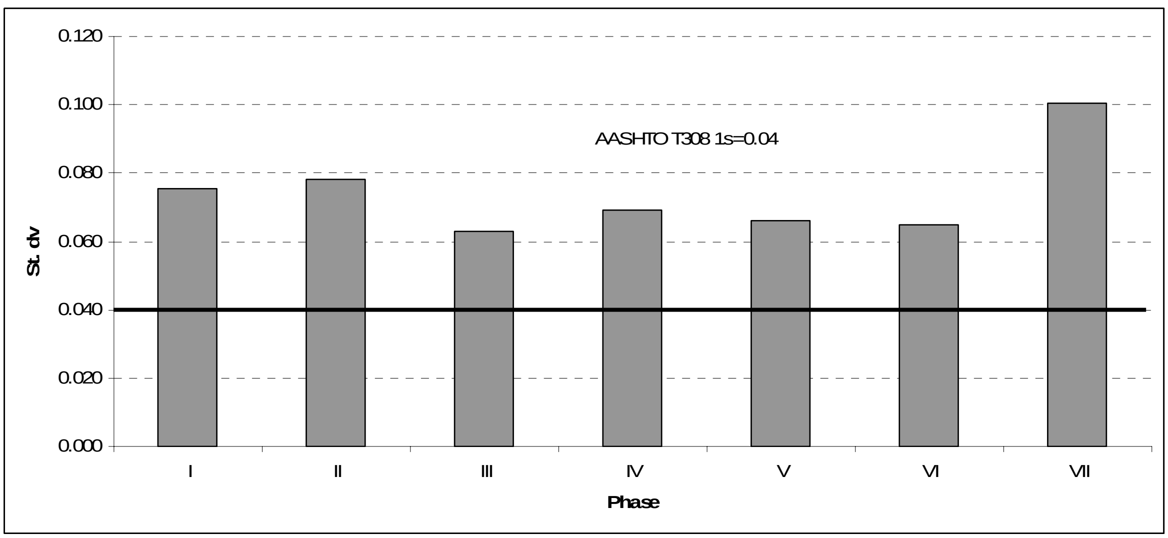

Figure 23. Percent Binder Testing Variation by Phase.

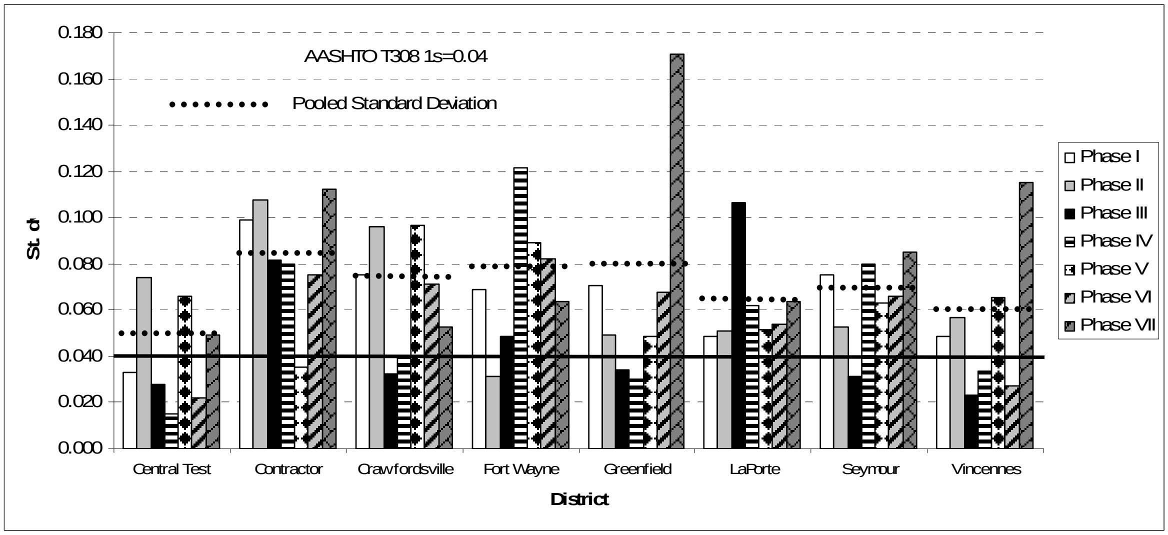

Figure 24. Percent Binder Testing Variation by District and Phase.

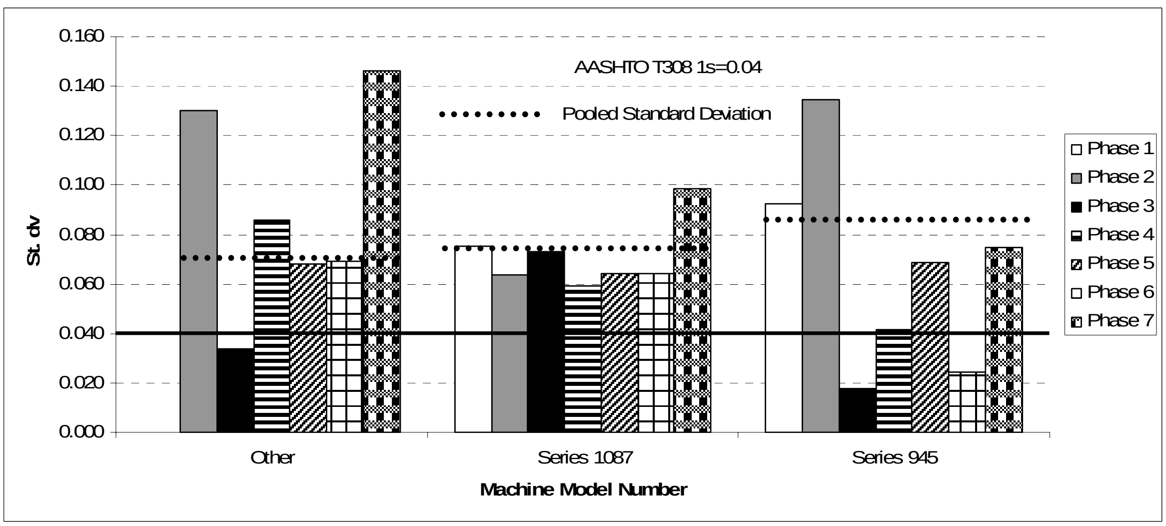

Figure 25. Percent Binder Testing Variation by Machine.

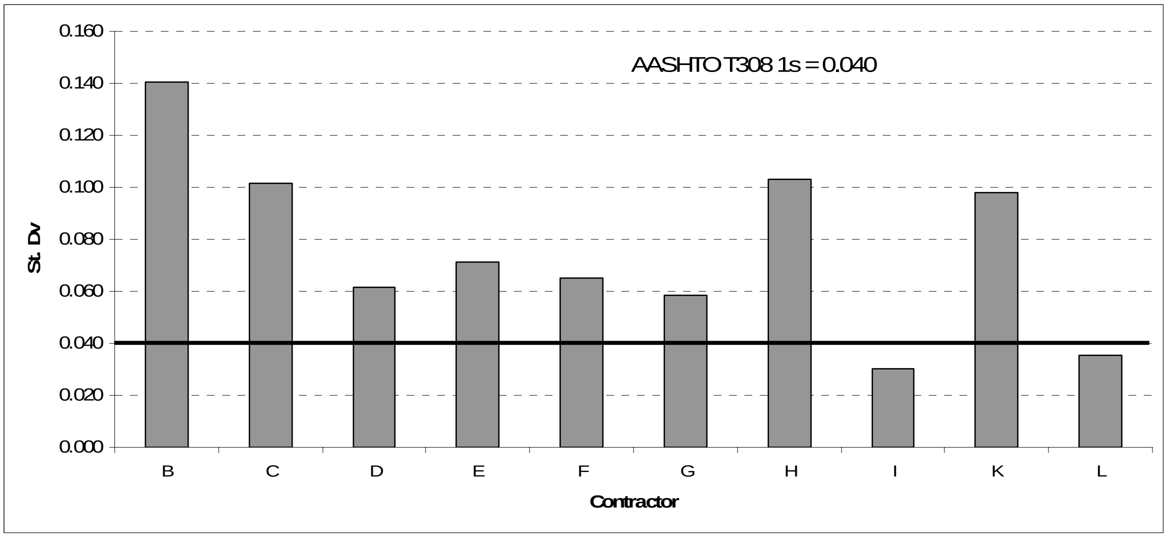

Figure 26. Percent Binder Testing Variation for Contractor Area Labs.

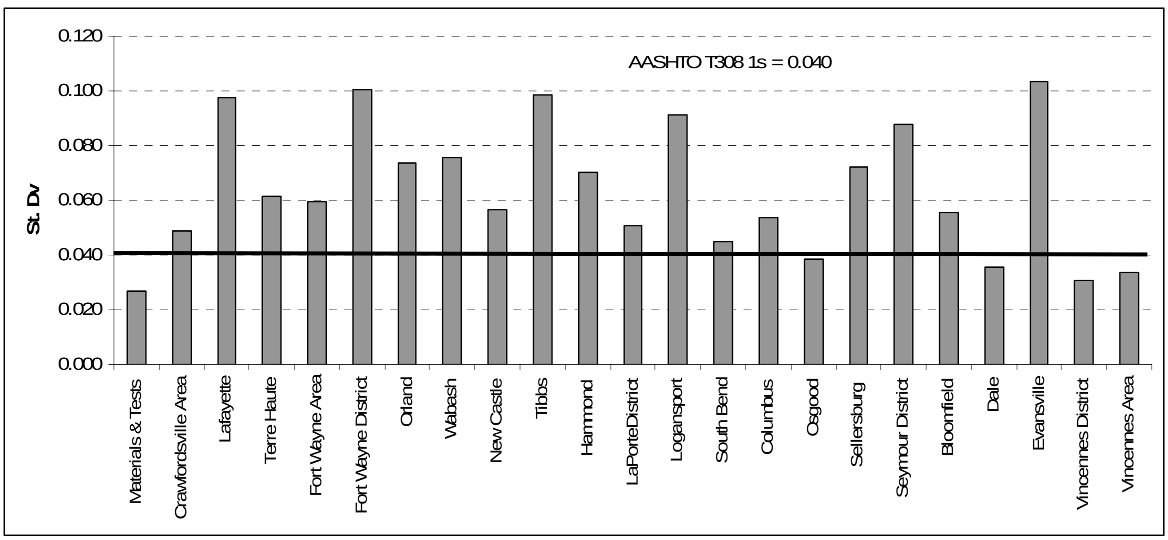

Figure 27. Percent Binder Testing Variation for State Area Labs.

The results indicate that in some cases the amount of variation decreased as the testing agencies became more familiar with the testing. The figures also show that the results are approaching the one-sigma limit of 0.06 for multi-laboratory testing. Table 40 shows the summary of the testing variation compared to the AASHTO T308 single operator one-sigma (1s) limit and multi-laboratory one-sigma (1s) limit. Overall, the contractor testing variation seems to be slightly larger than the state testing variation. The contractor variation exceeds the single-operator one-sigma limit by 233% and state testing by 155%.

The total variation for measuring binder content P_b including production variation was 0.233 (see Table 23) based on the analysis of volumetric data discussed in section 5.1. The isolated testing variation of 0.062 for the state is about 27% of the total variation.

Table 40. Summary of Material Variation

Testing Agency	n	Avg.	St.Dv	Single-operator (1s)	Multi-laboratory (1s)
Contractor	77	5.05	0.093	0.04	0.06
State	235	5.06	0.062	0.04	0.06

5.3 Analysis of Data Source III: INDOT Inter-Laboratory Exchange Data

5.3.1 A Description of Data Structure and Analysis Approach

This data source contains bulk specific gravity of aggregate and theoretical maximum specific gravity of HMA test data from the INDOT inter-laboratory exchange program. Data of bulk specific gravity of fine and coarse aggregate were collected between 1998 and 2002. Data of theoretical maximum gravity of the HMA was collected during 2000, 2001 and 2002. A summary of the data structure is given in Table 41.

The laboratories that were selected for testing varied from year to year and were not identified by the data source. Specimens were prepared in INDOT's central laboratory, and then sent to different laboratories for testing. The same samples were tested by different operators in different laboratories using different machines; each operator conducted two tests per sample except for the theoretical maximum specific gravity, which did not contain replicate measurements. AASHTO T209 test procedure was used in theoretical maximum gravity testing. The bulk specific gravity G_{sb}, the surface saturated bulk specific gravity SSD G_{sb}, the apparent specific gravity G_{sa} and water absorption were measured using AASHTO T84, 6.1.1 procedure for fine aggregate and AASHTO T85, 8.1 procedure for coarse aggregate. Table 42 displays the sampling procedures for the database.

Table 41. Summary of Data Structure

Number	Variable Name	No of Observations
1	Date	8
2	Lab	37
3	Replicate	2 (1,2) *
6	Samples	N=479

* G_{mm} testing did not include replicates

For the G_{mm} testing no sample fabrication variability (or very little) existed in this data source because the samples were fabricated in the same laboratory using the same materials for each testing cycle (date). The samples were then sent to the laboratories for testing. For aggregate specific gravity testing, the comparison of replicate tests removes the variation coming from varying aggregate sources (quarry) or obtaining aggregates from different parts of the quarry.

For the data analysis the variation between each replicate was then computed for specific gravities and water absorption. These variations were then grouped by test type and date. Using this information the pooled standard deviation was calculated for each test. For G_{mm} testing, data was analyzed by pooling all of the data within a given test date to compute the variation.

Table 42. Test Method and Sampling

Test Method	Parameter	Target value	Sampling
AASHTO T209	G_{mm}	Variable	X
AASHTO T84, 6.1.1	Fine aggregate G_{sb}	Variable	X*
	SSD G_{sb}	Variable	X*
	G_{sa}	Variable	X*
	Water abs.	Variable	X*
AASHTO T85, 8.1	Coarse aggregate G_{sb}	Variable	X*
	SSD G_{sb}	Variable	X*
	G_{sa}	Variable	X*
	Water abs.	Variable	X*

* Two replicate measurements.

5.3.2 Analysis Results for Descriptive Statistics

The following tables present the analysis results of the HMA inter-laboratory exchange database employing the analysis steps described above. The analyzed descriptive statistics were:

- Mean, Equation (1),
- Variance, Equation (2),
- Standard deviation, Equation (4), and

Coefficient of variation (percent), Equation (5)

Table 43 to 44 display the descriptive statistics for testing variability (S_{TE}) in the exchange data. Due to brevity the tables below present the variation only in the form of standard deviation omitting the variance to allow comparisons of the precision for each test method.

Table 43. Average Statistics for Coarse Aggregate Exchange Data.

Parameter	Avg	St.Dv	CV%	n
G_{sb}	2.617	0.009	0.351	19
SSD G_{sb}	2.646	0.010	0.350	28
G_{sa}	2.706	0.013	0.454	20
Water abs.	1.51	0.046	3.1	19

Table 44. Average Statistics for Fine Aggregate Exchange Data.

Parameter	Avg	St.Dv	CV%	n
G_{sb}	2.572	0.038	1.362	65
SSD G_{sb}	2.614	0.0299	1.075	65
G_{sa}	2.684	0.0264	0.873	65
Water abs.	1.59	0.41	21.8	65

Table 45. Average Statistics for Exchange Data Maximum Specific Gravity.

Parameter	Avg	St.Dv	CV%	n
G_{mm}	2.490	0.0172	0.625	133

Figure 28 to Figure 30 track the testing variation over the sampling dates. The data shows very little consistency from date to date. There is no notable learning curve present in the data.

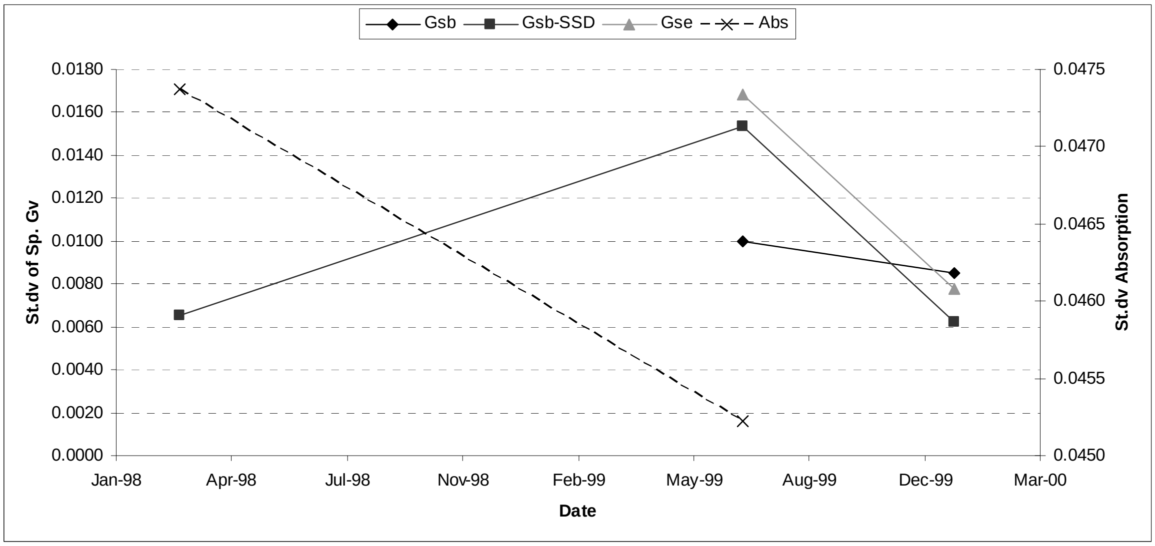

Figure 28. Coarse Aggregate Testing Variation.

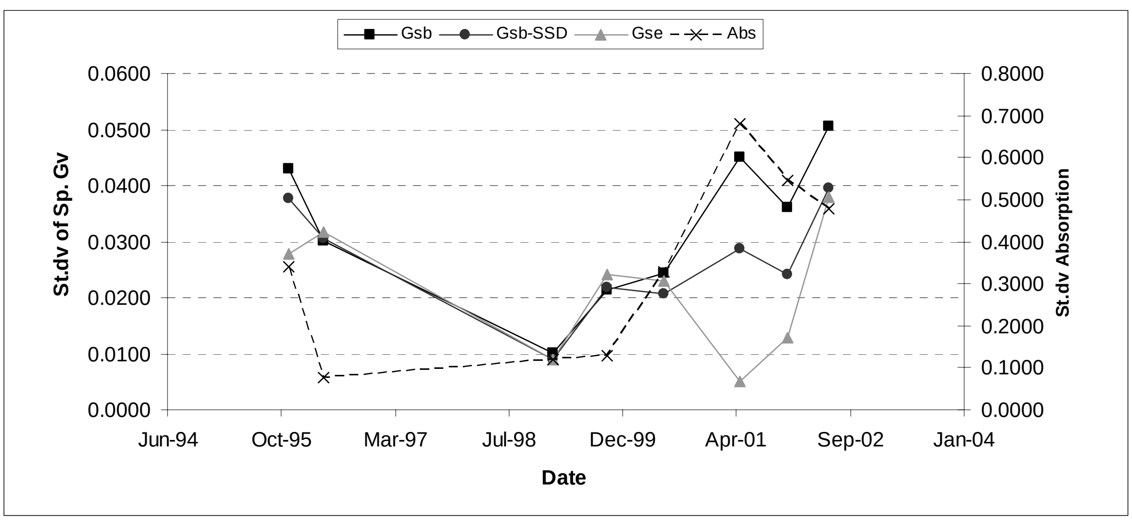

Figure 29. Fine Aggregate Testing Variation.

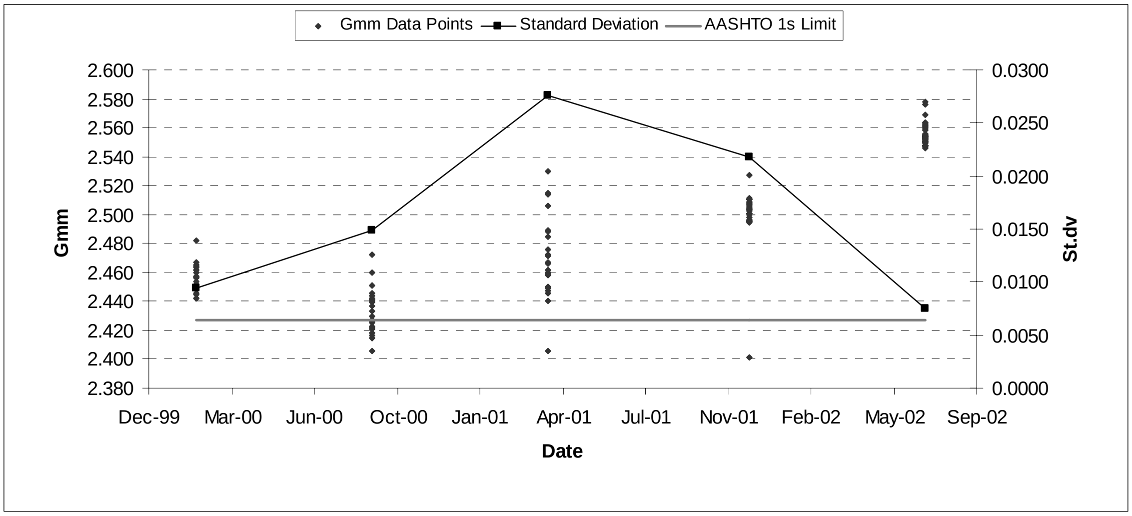

Figure 30. Maximum Specific Gravity Testing Variation.

5.3.3 Summary and Assessment of Precision

To assess the testing variation the pooled standard deviations were compared to the precision statements by the AASHTO specifications. The number of samples was not very large. A summary of the data is presented in Table 46 and in Figure 31. The fine aggregate specific gravity testing was noticeably variable than the allowed (1s) limits, while the coarse aggregate G_{sb} and water absorption were within the limits although the other parameters G_{sa} and SSD G_{sb} were not within limits.

Table 46. Summary of Material Variation

Test Method	Parameter	St.Dv	Single-operator 1s
AASHTO T209	G_{mm}	0.0172	0.0064*
AASHTO T84, 6.1.1	G_{sb}	0.038	0.011
	SSD G_{sb}	0.0299	0.0095
	G_{sa}	0.0264	0.0095
	Water abs.	0.41	0.11
AASHTO T85, 8.1	G_{sb}	0.009	0.009
	SSD G_{sb}	0.010	0.007
	G_{sa}	0.013	0.007
	Water abs.	0.046	0.088

*Multi-laboratory variation

The G_{mm} data also displays a high level of variability especially for the April 1 data set (see Figure 28). The total variability (S_T) with production variation obtained from the analysis of the volumetric database was 0.0154 (see Table 29) while the exchange database shows a pooled variation of 0.0172. This suggests that the analyzed exchange dataset may have included some erroneous data points.

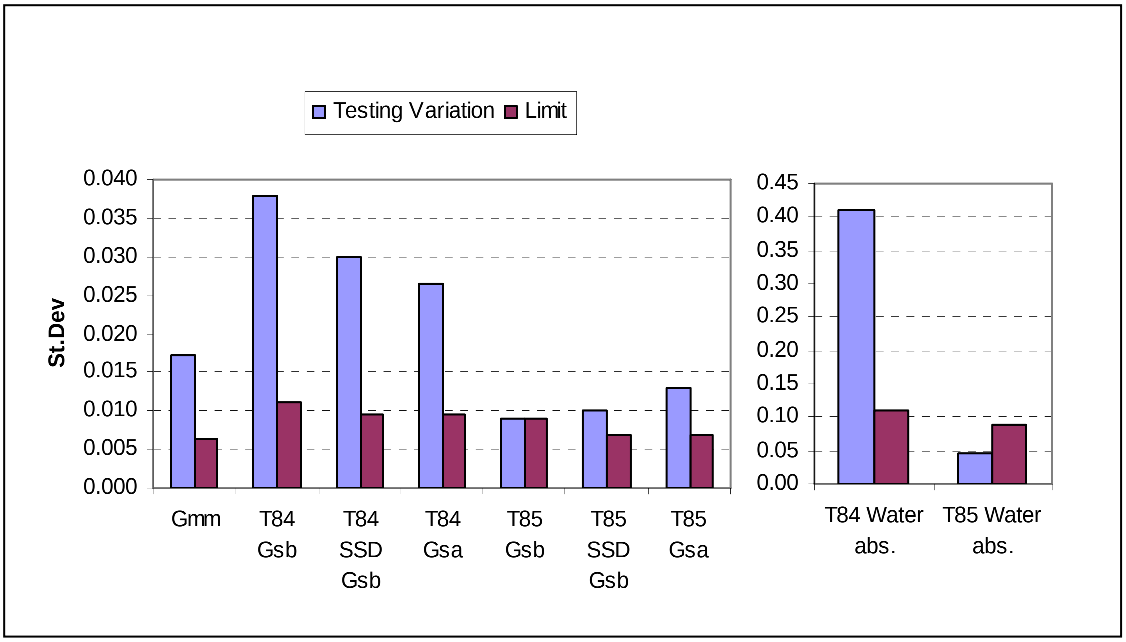

Figure 31. Summary of Aggregate Exchange Data.

5.4 Discussion of Analysis Results

The objective of existing data analysis was to assess the variability of INDOT QC/QA testing. The total variation including production and testing variation associated with different test methods was analyzed from the HMA volumetric acceptance data collected between 2001 and 2002. The data set included 118 different Job Mix Formulas (JMF) with approximately 15 to 20 plate samples in each JMF. The total number of data points was 4209 which includes the truck samples, plate samples, retesting and backup samples.

The following graphs present the target and tolerance values associated to each pay factor parameter in relation to the probability distribution functions (pdf) retrieved from the volumetric database. Figure 32 shows the pdf and pay factor limits for the gyratory compacted pill air voids content. From the pdf it can be estimated that approximately 26% of all gyratory compacted pills had air voids content less than 3% and about 7% of the pills had higher than 5% air voids content, thus being in the penalty range. In addition, about 38% of the pills were within the 5% bonus range.

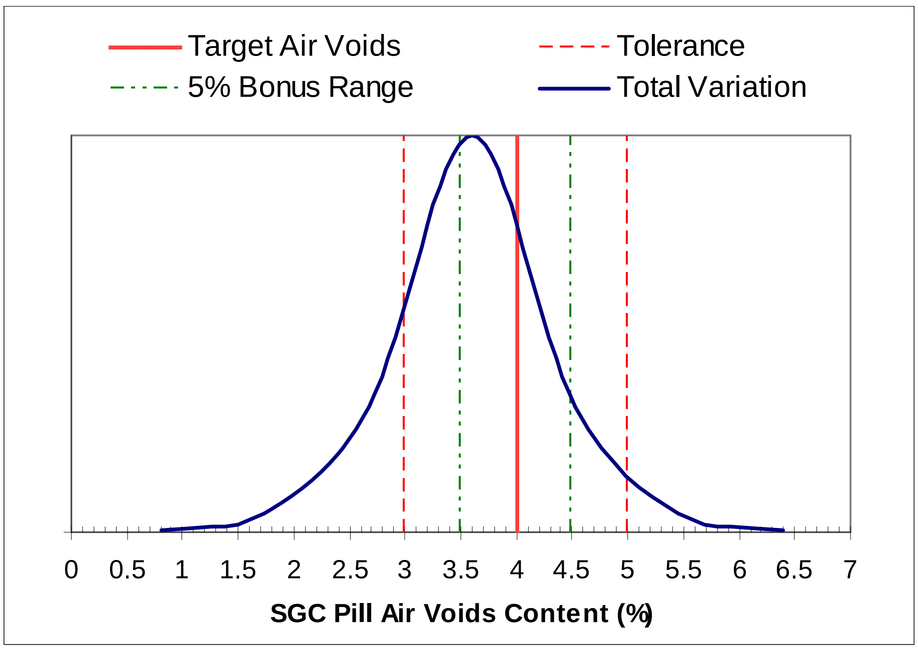

Figure 32. Pdf and Tolerances for SGC Pill Va.

This is illustrated below by calculating test statistics Z and probability associated to test statistics as follows. If X has a normal distribution with mean μ and standard deviation σ, then

$$Z = \frac{X - \mu}{\sigma} \tag{19}$$

has a standard normal distribution. Thus

$$P(a \le X \le b) = P\left(\frac{a-\mu}{\sigma} \le Z \le \frac{b-\mu}{\sigma}\right)$$
$$P(a \le X \le b) = P\left(\frac{b-\mu}{\sigma}\right) - P\left(\frac{a-\mu}{\sigma}\right) \quad (20)$$

<u>EXAMPLE</u>

The SGC pill air voids content full pay probability can be calculated by knowing the standard deviation σ and mean μ of the pdf. The target air void content is 4% and allowed variation is ±1.0%. Then

Lower tolerance limit = 4-1 = 3%

Higher tolerance limit = 4+1 = 5%

μ = 3.6%

σ = 0.93

$$P(3.0 \le X \le 5.0) = P\left(\frac{5.0-3.6}{0.93}\right) - P\left(\frac{3.0-3.6}{0.93}\right)$$
$$P(3.0 \le X \le 5.0) = .93 - .26$$
$$P(3.0 \le X \le 5.0) = 68\%$$

The value 0.68% present the area between limits *a* and *b* under the pdf curve shown in Figure 33. Then 100-68% = 32% which means that 32% of the test data is in the penalty range.

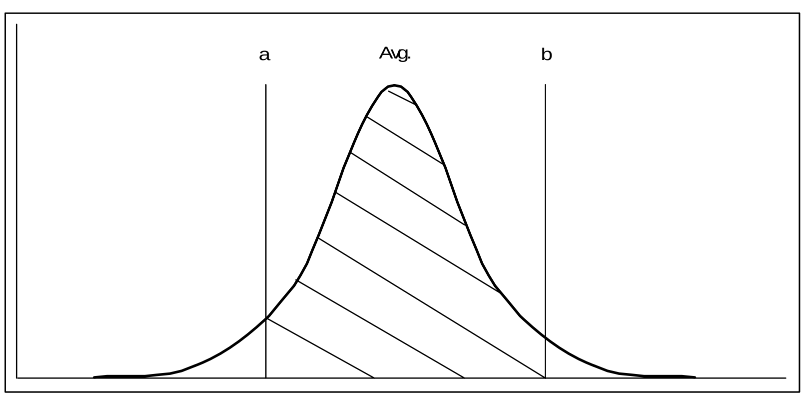

Figure 33. Normal Distribution Pdf.

Based on the overall variation (0.93%) of the SGC pill air voids content, the pill air voids content values ranged from 0 to 7%, as Figure 32 indicates. It is very unlikely that the production variation including raw material variation can explain such a large variation of the compacted mixture properties. Therefore, it is possible that there are other factors which are contributing to the variation, such as moisture in the mix, variation in gyratory compaction temperature, poorly calibrated gyratory, reheating of the mixture, etc. Therefore it is recommended that before applying any changes to the current specification limits a more thorough investigation of the causes of air voids variation be conducted.

Table 47 displays the probability (%) of a value to be within the target limits and the probability (%) of a value to be in the penalty range. The avg in the table refers to the μ, St. Dv refers to σ, and the lower and upper target ranges refer to *a* and *b*, respectively. The above example displays the calculations for the probability of a sample being within the target range for each pay factor.

Table 47. Percent within Limits and in the Penalty Range.

Test Method	Parameter	Pay Factor	Avg	St. Dv	Target Range		Within Limit (%)	Penalty Range (%)
					Lower	Upper		
ITM 586	Pb	Bonus	5.31	0.23	5.1	5.5	61	-
		Full Pay	5.31	0.23	4.8	5.8	97	3
AASHTO PP28	Pill Va	Bonus	3.60	0.93	3.5	4.5	38	-
		Full Pay	3.60	0.93	3.0	5.0	68	32
AASHTO PP28	Pill VMA	Bonus	14.06	0.6194	14.0	15.0	48	-
		Full Pay	14.06	0.6194	13.5	15.5	81	19
AASHTO T166	Core Density	Bonus	92.42	1.52	93.0	97.0	38	-
		Full Pay	92.42	1.52	92.0	97.0	61	39
AASHTO T275	Core Density	Bonus	91.12	1.41	93.0	97.0	9	-
		Full Pay	91.12	1.41	92.0	97.0	27	73

Similarly, Figure 34 illustrates that 19% of the gyratory compacted samples lie in the penalty range with 18% being below and 1% being above the target VMA ±1%. The overall target VMA was computed by averaging all VMA targets in the database.

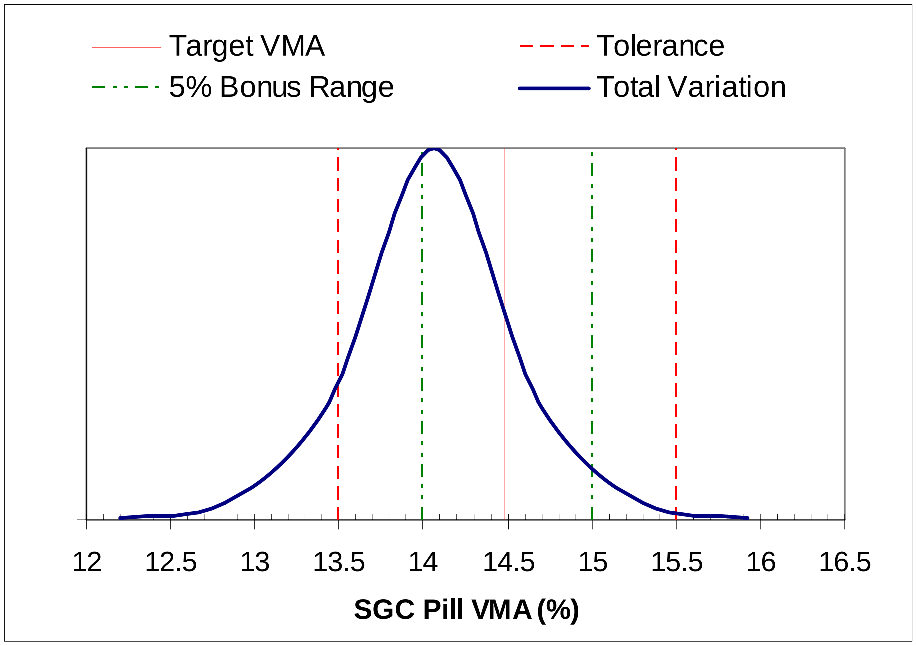

Figure 34. Pdf and Tolerances for SGC Pill VMA.

Figure 35 illustrates that about 3% of binder content data was in the penalty range. This is very typical distribution of statistical test data for the HMA because typically the production standard deviation for binder content is around $\sigma = 0.2$. Figure 35 gives the pdf distribution relative to the zero mean because volumetric database did not have target binder contests listed.

The interesting thing for the pavement density is that there are two target values listed in the INDOT specifications for the density, a full pay target density of 92.5% and a 5% bonus target density of 94%. Both targets are shown in Figure 36 and Figure 37. Figure 36 illustrates that 39% of the cores were in the penalty range for the pavement density measured with T166 test, and Figure 37 illustrates that 73% of the cores measured with T275 were in the penalty range. This of course is not desirable because if asphalt pavement has air voids content greater than 8% it is permeable for water. The figures clearly demonstrate that if target (92.5%) is set too close for the tolerance (92%) the probability of samples being in the penalty range increases with increasing standard deviation of the studied parameter. This means that if the standard deviation is high the “target” must be set further apart from the desired “average quality” that statistically the production is within the limits.

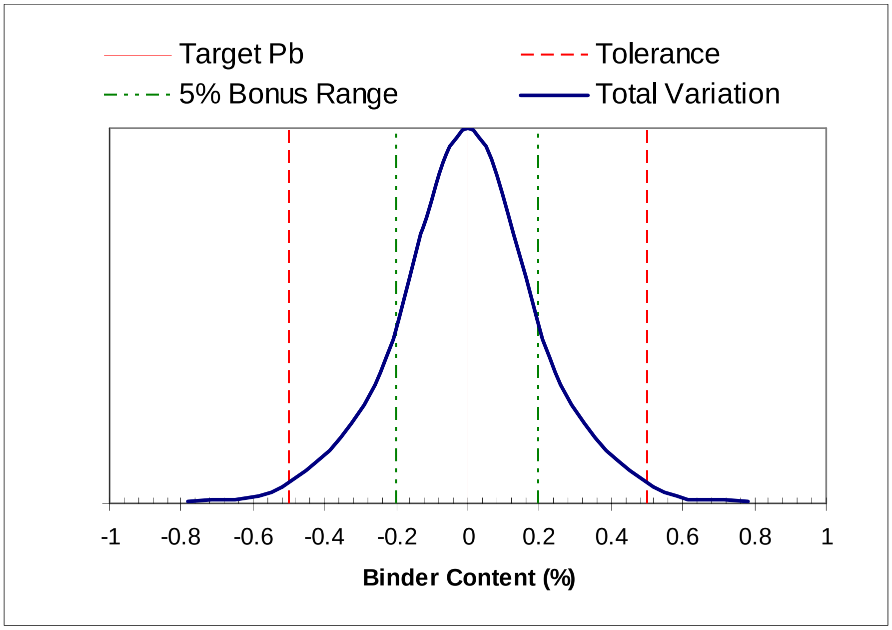

Figure 35. Pdf and Tolerances for Binder Content.

Overall it can be concluded that the hypothesis of increased testing variation associated with the calculated quantities, presented in the problem statement, turned out to be false. As discussed in Chapter 1 research has indicated (Hand and Epps, 2000) that the allowed variability in the materials testing can lead to unacceptable variation of the calculated quantities computed from the acceptable test results. Based on Monte Carlo simulation, the allowed variation in the tested bulk and theoretical maximum specific gravity values for asphalt concrete mixtures could produce unacceptable air void content variation. The simulation runs used ASTM precisions statements.

There are two reasons why this hypothesis turned out to be false. Firstly, an important change during the course of this research has taken place, namely, a change in the ASTM precision statements. A new 2004 version of the ASTM D2726 method which measures the bulk specific gravity of compacted mixture has a considerably tighter precision statement compared to the older version of the method. This is shown in Table 18 which compares the precision statement for calculated volumetric quantities. The new ASTM precision statement is now in agreement with the AASHTO precision statement.

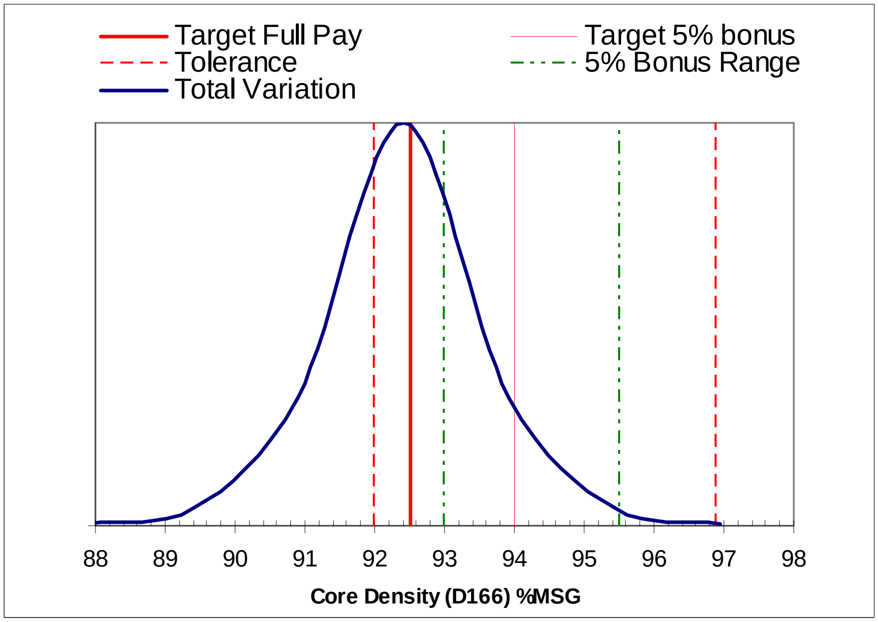

Figure 36. Psf and Tolerances for Density (T166 test).

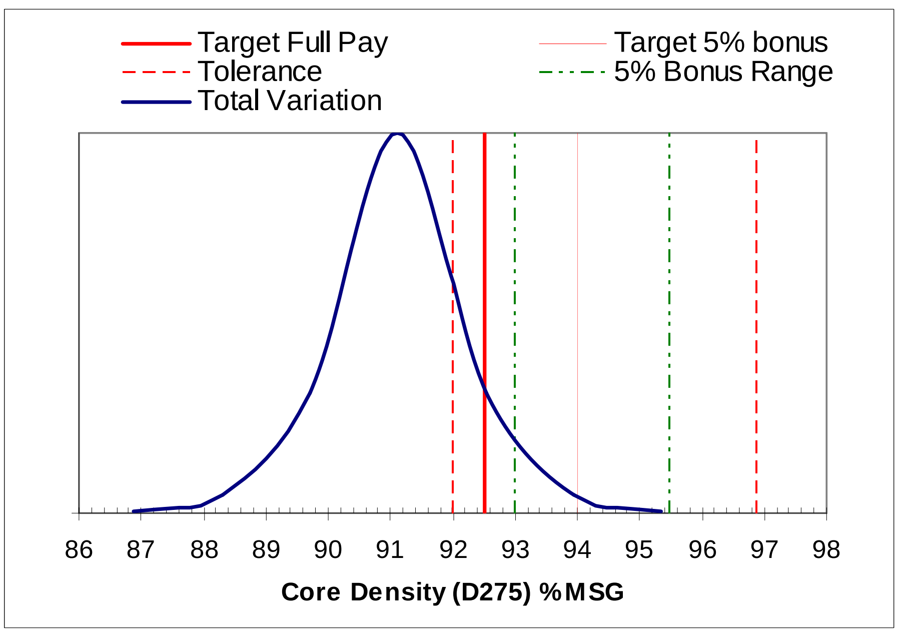

Figure 37. Psf and Tolerances for Density (T275 test).

The second thing is that the actual measured testing variation is smaller than was estimated based on the Monte Carlo simulation using "old" ASTM precision statements. This is illustrated in Figure 38 which shows that the probability of the pill air voids content being outside the tolerance limits of ±1% due to the testing errors is zero. The figure also shows that the measured and theoretical or allowed AASHTO (1) limits agree very well. The same applies for the pill VMA, which is shown in Figure 39, and for in-place density. The AASHTO (1s) VMA limit of 0.25 is quite tight as the Figure 38 indicates. However, this can be justified due to the fact that the variation in the VMA values is highly detrimental for the pavement performance in service.

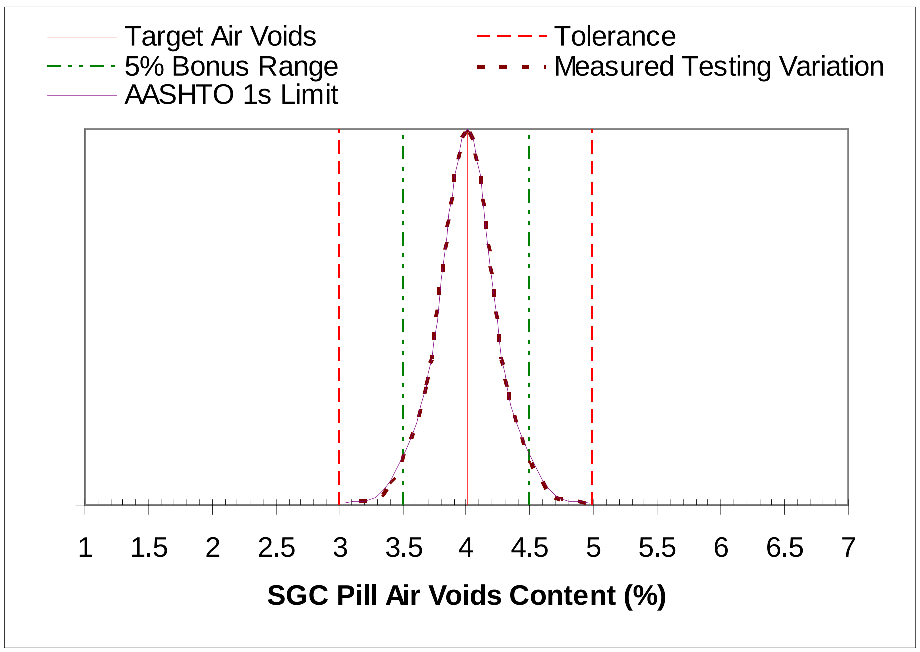

Figure 38. Measured and Theoretical Testing Variation.

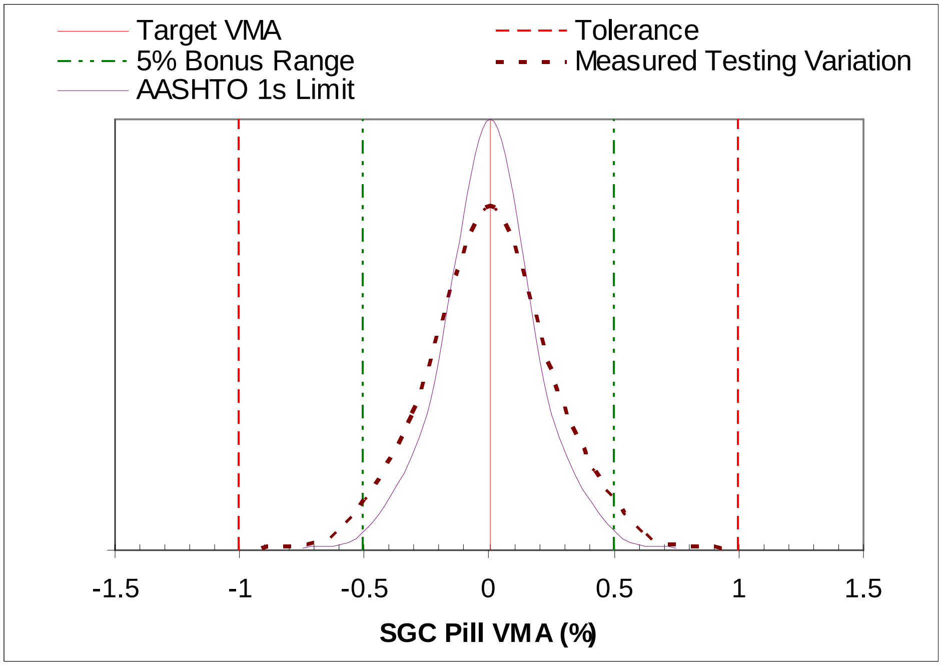

Figure 39. Measured and Theoretical Testing Variation.

6 HMA LABORATORY STUDY

6.1 Objective and Scope

Based on the analysis of existing INDOT HMA test data presented in the previous chapter, the variation of the aggregate specific gravity tests were not within the allowable testing variation limits. In addition, the variation of mixture maximum specific gravity could not be adequately assessed due to the lack of data. Therefore, the objective of this laboratory study was to quantify the testing variation of these test methods and also assess the inherent material variation, if possible, by including aggregates with varying specific gravities and water absorption values in the tested materials. It was hypothesized that the inherent material variability is caused by the varying water absorption and specific gravity of the aggregates used in the HMA mixtures. The laboratory study, therefore, consisted of the following test methods:

1. Maximum specific gravity of mixture, G_{mm}
2. Bulk Specific Gravity of fine aggregate, G_{sb} and water absorption
3. Bulk Specific Gravity of coarse aggregate, G_{sb} and water absorption

In addition to the traditional AASHTO test methods, a new vacuum based Instrotek Corelok test method was used in the study. Test results were analyzed first by producing descriptive statistics by the means of plotting the data and computing averages and standard deviations. Additional analysis was conducted using nested factorial Analysis of Variance (ANOVA) method.

6.2 Description of Tested Aggregates

The aggregate selection was based upon a desire for the aggregates to represent a broad range of material properties. The focus of these properties was the water absorption and specific gravities of the aggregates. It was believed that the variation of aggregate properties may impact the repeatability of the specific gravity testing. Working with INDOT personnel from Materials and Tests the desired aggregates were obtained from various sources in Indiana and are listed in Table 48. Appendix A and B give gradations and photos of the tested aggregates. The two fine aggregates were selected to investigate if there is a difference in the repeatability of testing natural sand versus manufactured sand. With the coarse aggregates it was desirable to obtain one intermediately absorptive aggregate as a benchmark. From there four more aggregates were selected because of their relatively high or low absorption and specific gravity values.

Table 48. Description of Tested Aggregates.

	Materials	CA Source #	Specific Gravity	Absorption	Supplier
Fine Agg.	Natural Sand	2183	-	-	Vulcan Materials
	Manufactured Sand	2312	-	-	Hanson Aggregates
Coarse Agg.	Limestone	2314	Intermediate	Intermediate	Martin Marietta
	Dolostone	2421	High	Low	U.S. Aggregates, Inc.
	Dolostone	2551	Low	High	Hanson Aggregates
	Blast Furnace Slag	2451	Low	High	The Levy Company, Inc.
	Steel Slag	2451	High	Low	The Levy Company, Inc.

6.3 Factorial Design

The laboratory study was carefully designed so that the testing variation of each of the test methods could be measured along with the inherent material variation. The three tests that required further investigation for the bituminous materials testing were:

- Specific Gravity and Absorption of Coarse Aggregate (AASHTO T 85, and Corelok Procedure)
- Specific Gravity and Absorption of Fine Aggregate (AASHTO T 84, and Corelok Procedure)
- Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures (AASHTO T 209, and Corelok Procedure).

All of the tests were preformed following a similar layout. Each test consisted of a number of samples that were each split down into two replicates. Each batch was prepared separately, however it was assumed that there was no material variation between batches. The hypothesis was that because none of the tests were destructive each sample could be retested so that the testing variation and inherent material variation could be assessed.

Taking advantage of this each of the replicates was tested using each method of testing three times.

The variability in fine and coarse aggregate specific gravity testing was conducted by again varying equipment used to conduct the testing, with different types of aggregate. Both fine and coarse aggregates were tested using both the AASHTO T84 and T85 standard and the Instrotek Corelok testing procedures. This is summarized in Table 49 and Table 50.

Table 49. Testing Plan for Fine Aggregate Specific Gravity Testing.

Source #	Test Method /Parameters	Number of Replicates	Number of Tests	Test Repeated	Total Number of Tests
2183	AASHTO T84, Corelok/ Gsb, Gse, Gsa, w-abs%	2	2	3	24
2312					

Table 50. Testing Plan for Coarse Aggregate Specific Gravity Testing.

Source #	Test Method /Parameters	Number of Replicates	Number of Tests	Test Repeated	Total Number of Tests
2314	AASHTO T85, Corelok/ Gsb, Gse, Gsa, w-abs%	2	2	3	60
2421					
2551					
2451-Steel Slag					
2451-Blast Furnace Slag					

There are four different asphalt mixes that were tested for maximum specific gravity. These mixes can be found in Table 51. Aggregate blending was done varying coarse aggregate properties from very little water absorption to high water absorption. Aggregate blends are given in Appendix? Due to the limited number of aggregate stockpiles and stockpile gradations used to blend the mixtures, the gradations turned out to be open graded. However, this does not affect the goal of studying the influence of water absorption on measured specific gravity. Binder content for each mix was selected based on the INDOT specifications for open graded mixtures and using visual judgment of a good coating of aggregate after mixing. Testing of these mixes was done using both the standard and supplemental procedures according to AASHTO T209 as well as an Instrotek Corelok machine. This is summarized in Table 52.

Table 51. Description of Tested Mixtures.

Mix #	Pb	Fine Aggregate		Coarse Aggregate			
		Source #	Name	Source #	Name	Specific Gravity	Absorption
Mix 1	3.0	2183	Natural Sand	2421	Dolostone	Intermediate	Low
Mix 2	3.3	2183	Natural Sand	2551	Dolostone	Low	High
Mix 3	3.3	2183	Natural Sand	2451	Blast Furnace Slag	Intermediate	High
Mix 4	4	2183	Natural Sand	2451	Steel Slag	High	Low

Table 52. Testing Plan for Maximum Specific Gravity Test.

Mix #	Test Method /Parameters	Number of Replicates	Number of Tests	Test Repeated	Total No of Tests
Mix #1	AASHTO T209, Corelok/ Gmm	2	2	3	48
Mix #2					
Mix #3					
Mix #4					

6.4 Test Results and Descriptive Statistics

6.4.1 Specific Gravity and Absorption of Fine Aggregates

The tabulated analysis results are shown in Table 53 through Table 56. Figure 38 through Figure 47 display the results in graphical form. Additional information including pictures of aggregates and the original test data can be found in Appendix B and D. The fine aggregate data was analyzed by computing variation of each aggregate and generating the average (mean) of all the test data for both test methods T84 and Corelok. This is shown in each of the tables in columns labeled as “All”. The data was then analyzed by comparing the standard deviation between the two replicates for each iteration of the test. Therefore the first test result for each replicate for each test was compared, then the second and so on. These variances were then used to calculate a pooled standard deviation for each aggregate and test method. This is shown in columns labeled as “Replicates” in the tables. Finally, the data was analyzed comparing retests. This was done by computing the variance between each replicate and then compiling them to create a pooled standard deviation for each aggregate and test method. This is shown in columns labeled as “Retests” in the tables. The tables also show the overall variation for each test method over each aggregate tested. This is shown in the last row labeled as “ALL”.

The test results showed an increasing trend in the testing variation when replicates and retests were compared. To study more of this phenomenon, an additional calculation was done to compare the first test of the two replicate specimens. This is labeled as “First Two Rep. in the tables. By comparing the averages of the first two tests to the averages obtained from all testing, there seems to be an increasing trend in the bulk specific gravity and water absorption values. It can be speculated that subsequent testing of the same sample caused some physical changes or degradation of the tested samples.

Table 53. Percent Absorption of Fine Aggregates.

Source Agg. #	Test	All		First Two Rep.		Rep.	Retest
		Avg	St dev	Avg	St dev	St dev	St dev
2183 (Nat)	Corelok	1.68	0.352	1.38	0.569	0.329	0.363
2183 (Nat)	T 84	1.61	0.136	1.68	0.106	0.118	0.113
2312 (Man)	Corelok	1.15	0.379	1.63	0.059	0.056	0.424
2312 (Man)	T 84	1.85	0.151	2.01	0.042	0.077	0.165
ALL	Corelok	1.42	0.365	1.51	0.405	0.193	0.393
ALL	T 84	1.73	0.144	1.84	0.081	0.098	0.139

Table 54. Apparent Specific Gravity of Fine Aggregates.

Source Agg. #	Test	All		First Two Rep.		Rep.	Retest
		Avg	St dev	Avg	St dev	St dev	St dev
2183 (Nat)	Corelok	2.728	0.0021	2.729	0.0021	0.0024	0.0023
2183 (Nat)	T 84	2.720	0.0019	2.719	0.0011	0.0017	0.0021
2312 (Man)	Corelok	2.748	0.0026	2.748	0.0028	0.0020	0.0025
2312 (Man)	T 84	2.733	0.0061	2.729	0.0045	0.0056	0.0061
ALL	Corelok	2.738	0.0023	2.738	0.0025	0.0022	0.0024
ALL	T 84	2.727	0.0040	2.724	0.0033	0.0036	0.0041

Table 55 Bulk Specific Gravity SSD of Fine Aggregates.

Source Agg. #	Test	All		First Two Rep.		Rep.	Retest
		Avg	St dev	Avg	St dev	St dev	St dev
2183 (Nat)	Corelok	2.652	0.0163	2.666	0.0269	0.0158	0.0171
2183 (Nat)	T 84	2.648	0.0060	2.644	0.0056	0.0053	0.0050
2312 (Man)	Corelok	2.695	0.0175	2.673	0.0057	0.0044	0.0195
2312 (Man)	T 84	2.650	0.0104	2.639	0.0023	0.0071	0.0116
ALL	Corelok	2.673	0.0169	2.670	0.0194	0.0101	0.0183
ALL	T 84	2.649	0.0082	2.641	0.0043	0.0062	0.0083

Table 56. Bulk Specific Gravity of Fine Aggregates.

Source Agg. #	Test	All		First Two Rep.		Rep.	Retest
		Avg	St dev	Avg	St dev	St dev	St dev
2183 (Nat)	Corelok	2.608	0.0251	2.630	0.0410	0.0239	0.0261
2183 (Nat)	T 84	2.606	0.0093	2.600	0.0082	0.0081	0.0077
2312 (Man)	Corelok	2.664	0.0272	2.630	0.0071	0.0057	0.0303
2312 (Man)	T 84	2.602	0.0138	2.587	0.0012	0.0086	0.0154
ALL	Corelok	2.636	0.0261	2.630	0.0294	0.0148	0.0282
ALL	T 84	2.604	0.0115	2.593	0.0059	0.0084	0.0115

Figure 40 to Figure 43 compare the means (averages) of different aggregates and test methods. The figures also show the 2 sigma error bar for the mean calculated from the overall standard deviation of each test case. Some conclusions can be made based on the error bar of the significance of the observed differences. As an example, the error bars for FA # 2183 natural sand, shown in Figure 40, suggest that the difference between the means of apparent specific gravity values measured by T84 and Corelok is statistically significant at 95% confidence level because the error bars do not overlap. However, based on the error bars in the other figures the rest of the results are not statistically different. The figures also show that the T84 and Corelok give more consistent test results for the natural sand compared to the manufactured sand. For the manufactured sand the difference in test results between T84 and Corelok seems to be statistically insignificant.

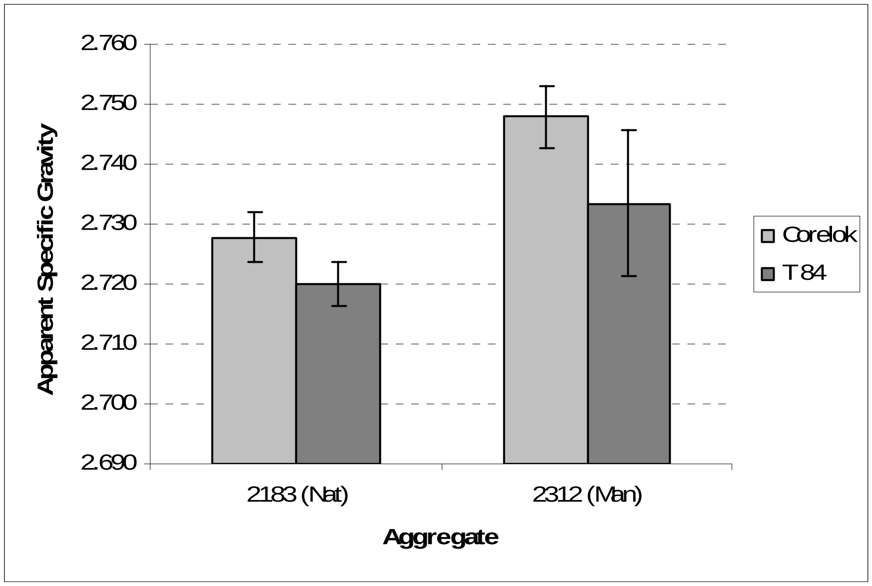

Figure 40. Fine Aggregate Apparent Specific Gravity (Means).

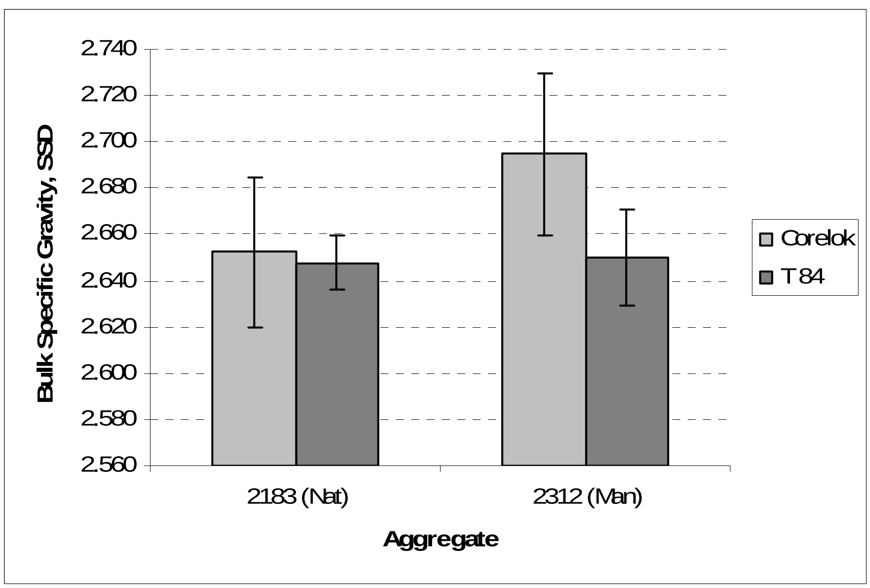

Figure 41. Fine Aggregate Bulk Specific Gravity, SSD (Means).

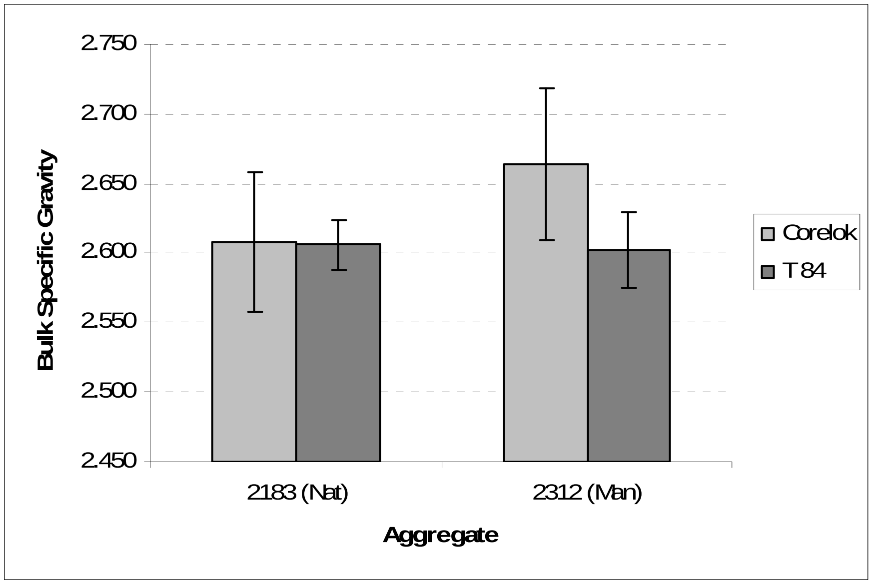

Figure 42. Fine Aggregate Bulk Specific Gravity (Means).

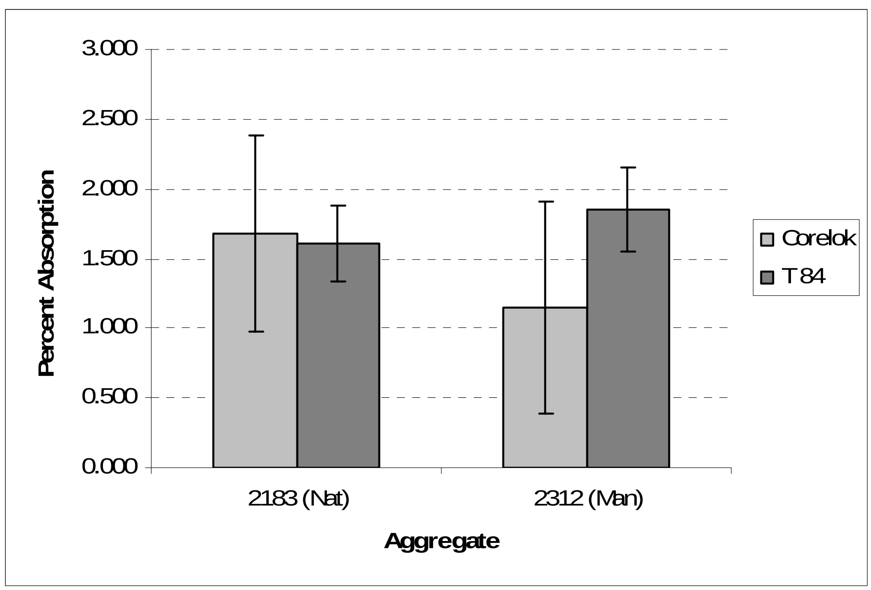

Figure 43. Fine Aggregate Percent Absorption (Means).

Testing variation in terms of standard deviation is shown in Figure 44 to Figure 47. Due to the sample degradation during testing, as discussed above, only testing variation obtained from the replicates is comparable to the specification limits and all statements of testing variation refer to the replicate testing. The testing variation of all of the AASHTO

T84 tests was at or below the (1s) testing limit. The Corelok was above the (1s) AASHTO T84 limit in all the measured categories except for the apparent specific gravity.

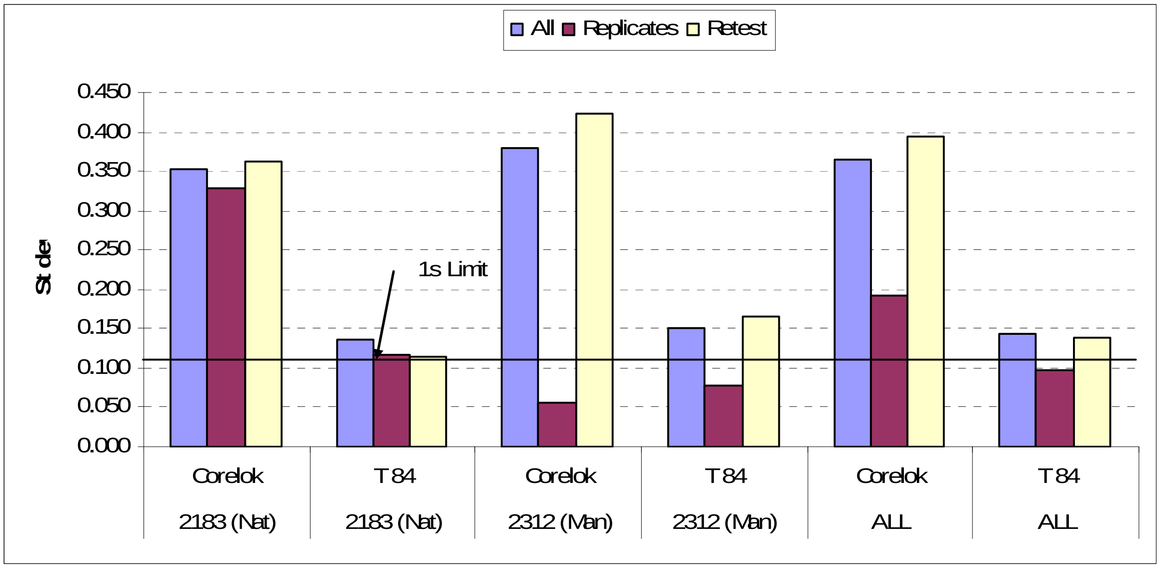

Figure 44. Fine Aggregate Percent Absorption (Standard Deviations).

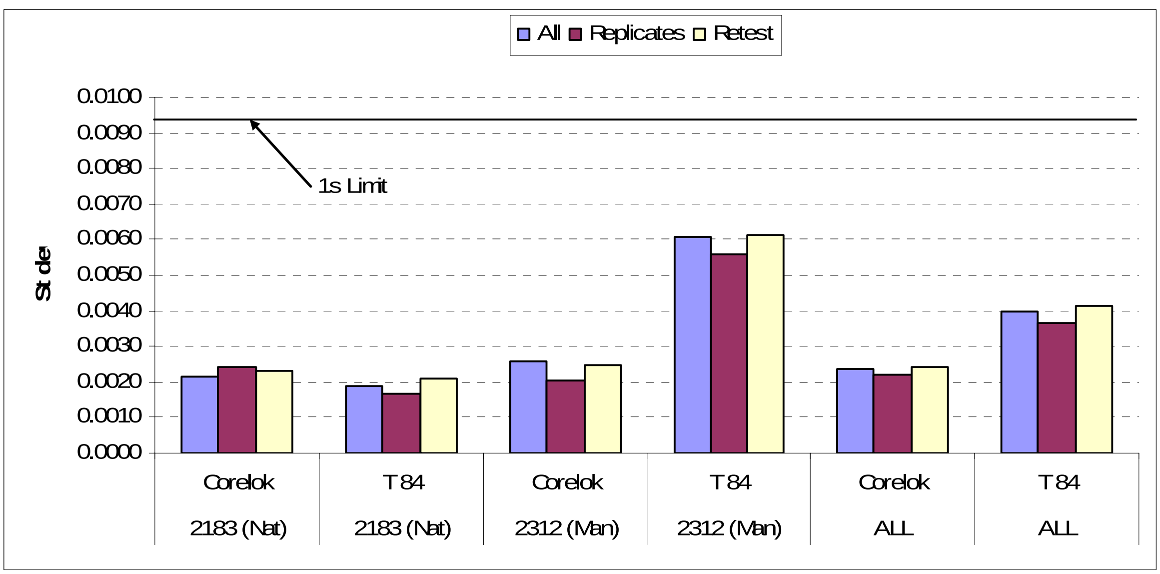

Figure 45. Fine Aggregate Apparent Specific Gravity (Standard Deviations).

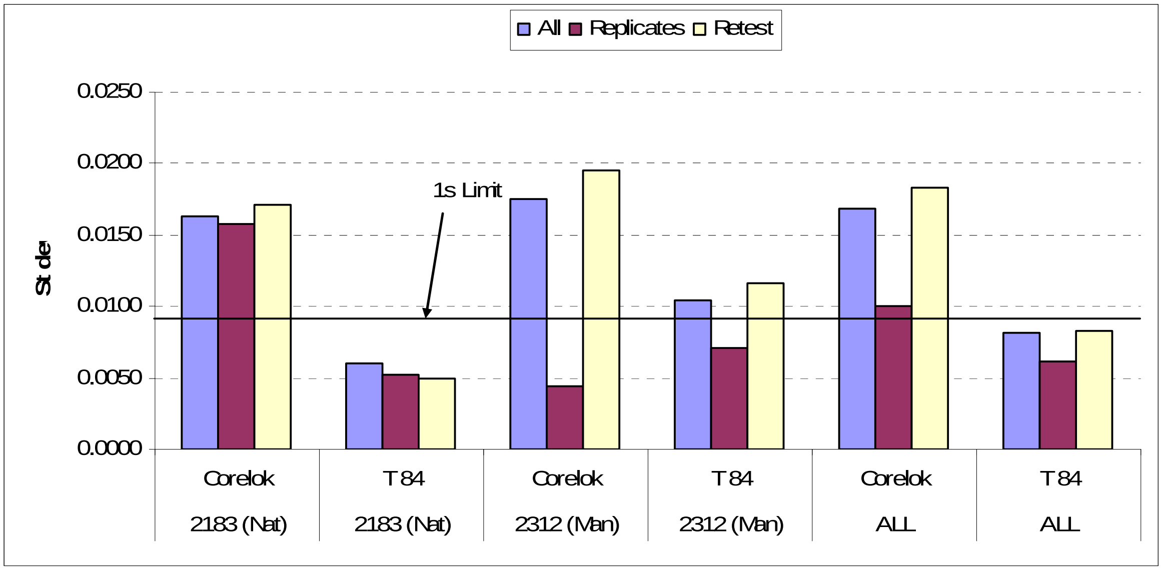

Figure 46. Fine Aggregate Bulk Specific Gravity SSD (Standard Deviations).

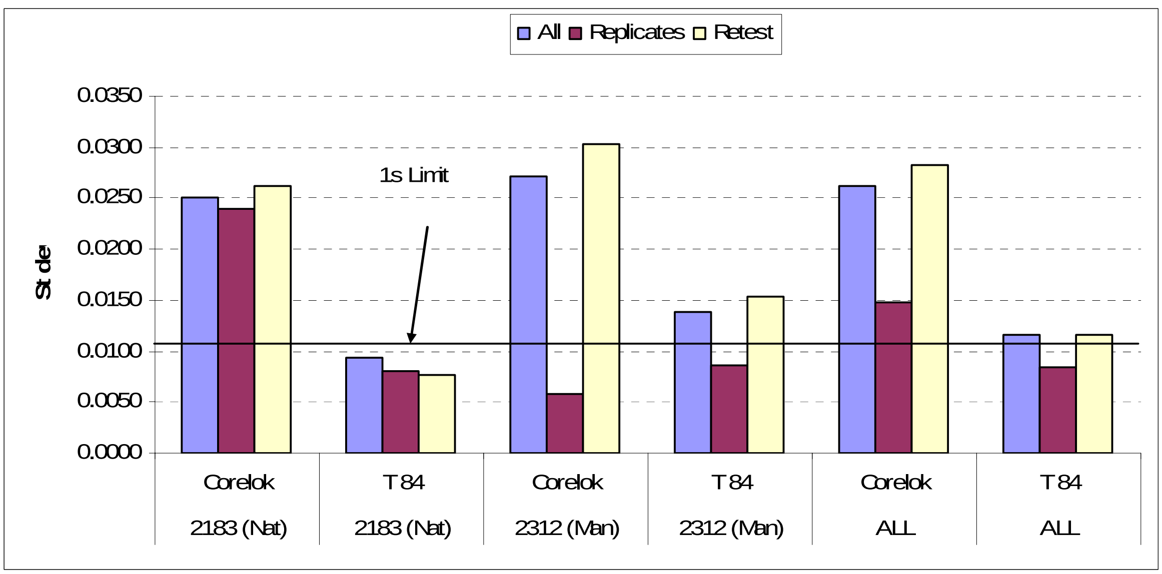

Figure 47. Fine Aggregate Bulk Specific Gravity (Standard Deviations).

6.4.2 Specific Gravity and Absorption of Coarse Aggregates

The coarse aggregate data was analyzed in a similar manner as the fine aggregate. The results from this analysis can be found in Table 57 through Table 60. Figure 48 through Figure 55 display the results from the analysis. Additional information including the original data can be found in Appendix A and E.

Table 57. Percent Absorption of Coarse Aggregate.

Source Agg. #	Test	All		First Two Rep.		Rep.	Retest
		Avg	St Dev	Avg	St Dev	St Dev	St Dev
2314	Corelok	0.441	0.065	0.430	0.086	0.071	0.073
2314	T 85	1.567	0.115	1.448	0.069	0.067	0.118
2421	Corelok	0.419	0.122	0.299	0.139	0.083	0.126
2421	T 85	1.159	0.135	1.056	0.007	0.022	0.150
2551	Corelok	3.550	1.450	4.952	2.147	1.240	1.495
2551	T 85	4.215	0.476	3.612	0.027	0.034	0.532
2451-BF	Corelok	5.463	1.388	6.761	2.099	1.236	1.344
2451-BF	T 85	5.828	0.766	4.955	0.441	0.313	0.853
2451-SS	Corelok	0.825	0.061	0.827	0.066	0.069	0.063
2451-SS	T 85	1.823	0.199	1.737	0.220	0.184	0.212
All	Corelok	2.139	0.617	2.653	1.345	0.540	0.620
All	T 85	2.918	0.338	2.562	0.223	0.124	0.373

Table 58. Apparent Specific Gravity of Coarse Aggregate.

Source Agg. #	Test	All		First Two Rep.		Rep.	Retest
		Avg	St Dev	Avg	St Dev	St Dev	St Dev
2314	Corelok	2.710	0.0045	2.713	0.0028	0.0017	0.0049
2314	T 85	2.703	0.0025	2.700	0.0015	0.0015	0.0025
2421	Corelok	2.797	0.0553	2.753	0.0976	0.0564	0.0555
2421	T 85	2.801	0.0056	2.795	0.0026	0.0033	0.0057
2551	Corelok	2.837	0.0023	2.836	0.0014	0.0027	0.0016
2551	T 85	2.710	0.0288	2.675	0.0011	0.0103	0.0318
2451-BF	Corelok	2.882	0.1102	2.978	0.1810	0.1047	0.1134
2451-BF	T 85	2.616	0.0571	2.544	0.0152	0.0140	0.0627
2451-SS	Corelok	3.596	0.0085	3.601	0.0085	0.0072	0.0094
2451-SS	T 85	3.548	0.0097	3.538	0.0032	0.0038	0.0106
All	Corelok	2.964	0.0362	2.976	0.0921	0.0345	0.0370
All	T 85	2.876	0.0207	2.850	0.0071	0.0066	0.0227

Figure 47 to Figure 50 compare the means (averages) of different aggregates and test methods. Figures also show the 2 sigma error bar for the mean. Based on the information obtained from the INDOT aggregate database, the two most absorptive aggregates were the blast furnace slag CA #2451 and Dolostone # 2551. These tests shown in the tables above are in agreement with the INDOT database. The Steel slag CA # 2451 had the highest specific gravity, as expected. The second heaviest aggregate based on INDOT database should have been the Dolostone CA # 2421, which turned out to be true based on T85 testing but not based on the Corelok testing. The INDOT database contains test results conducted with AASHTO test methods which explain the good agreement to the T85 testing. Figures also show that the Corelok gave systematically higher specific gravity values and lower absorption values compared to the T85 testing.

Table 59. Bulk Specific Gravity, SSD of Coarse Aggregate.

Source Agg. #	Test	All		First Two Rep.		Rep.	Retest
		Avg	St Dev	Avg	St Dev	St Dev	St Dev
2314	Corelok	2.690	0.0035	2.693	0.0014	0.0019	0.0039
2314	T 85	2.634	0.0040	2.636	0.0044	0.0039	0.0030
2421	Corelok	2.776	0.0495	2.739	0.0898	0.0519	0.0498
2421	T 85	2.745	0.0053	2.743	0.0028	0.0024	0.0055
2551	Corelok	2.671	0.0603	2.612	0.0877	0.0507	0.0618
2551	T 85	2.534	0.0120	2.528	0.0001	0.0085	0.0126
2451-BF	Corelok	2.623	0.0285	2.642	0.0481	0.0315	0.0317
2451-BF	T 85	2.402	0.0262	2.371	0.0011	0.0107	0.0284
2451-SS	Corelok	3.521	0.0046	3.526	0.0021	0.0024	0.0051
2451-SS	T 85	3.393	0.0124	3.391	0.0204	0.0144	0.0117
All	Corelok	2.856	0.0293	2.842	0.0601	0.0277	0.0304
All	T 85	2.741	0.0120	2.734	0.0094	0.0080	0.0122

Table 60. Bulk Specific Gravity of Coarse Aggregate.

Source Agg. #	Test	All		First Two Rep.		Rep.	Retest
		Avg	St Dev	Avg	St Dev	St Dev	St Dev
2314	Corelok	2.678	0.0042	2.682	0.0035	0.0035	0.0046
2314	T 85	2.593	0.0067	2.599	0.0061	0.0056	0.0059
2421	Corelok	2.764	0.0464	2.731	0.0856	0.0495	0.0466
2421	T 85	2.713	0.0079	2.715	0.0030	0.0021	0.0087
2551	Corelok	2.580	0.0922	2.490	0.1344	0.0776	0.0947
2551	T 85	2.432	0.0133	2.439	0.0007	0.0083	0.0140
2451-BF	Corelok	2.488	0.0179	2.476	0.0035	0.0197	0.0138
2451-BF	T 85	2.269	0.0184	2.259	0.0105	0.0141	0.0201
2451-SS	Corelok	3.492	0.0046	3.497	0.0000	0.0029	0.0048
2451-SS	T 85	3.332	0.0180	3.333	0.0273	0.0200	0.0177
All	Corelok	2.800	0.0330	2.775	0.0713	0.0307	0.0329
All	T 85	2.668	0.0129	2.669	0.0134	0.0100	0.0133

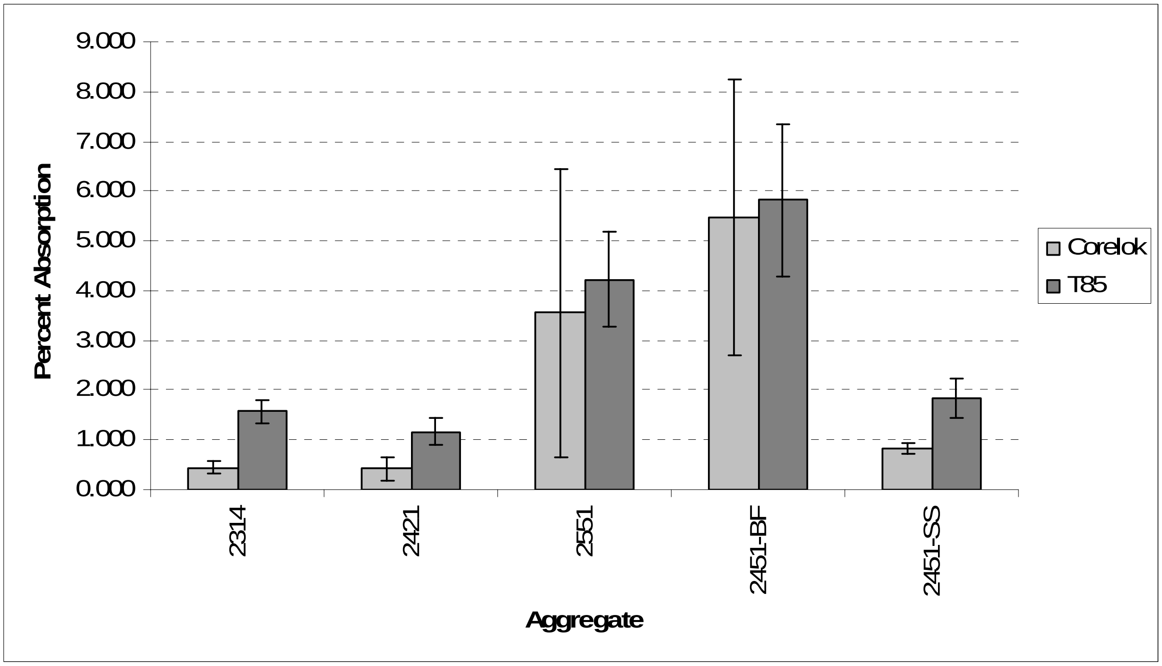

Figure 48. Coarse Aggregate Percent Absorption (Means).

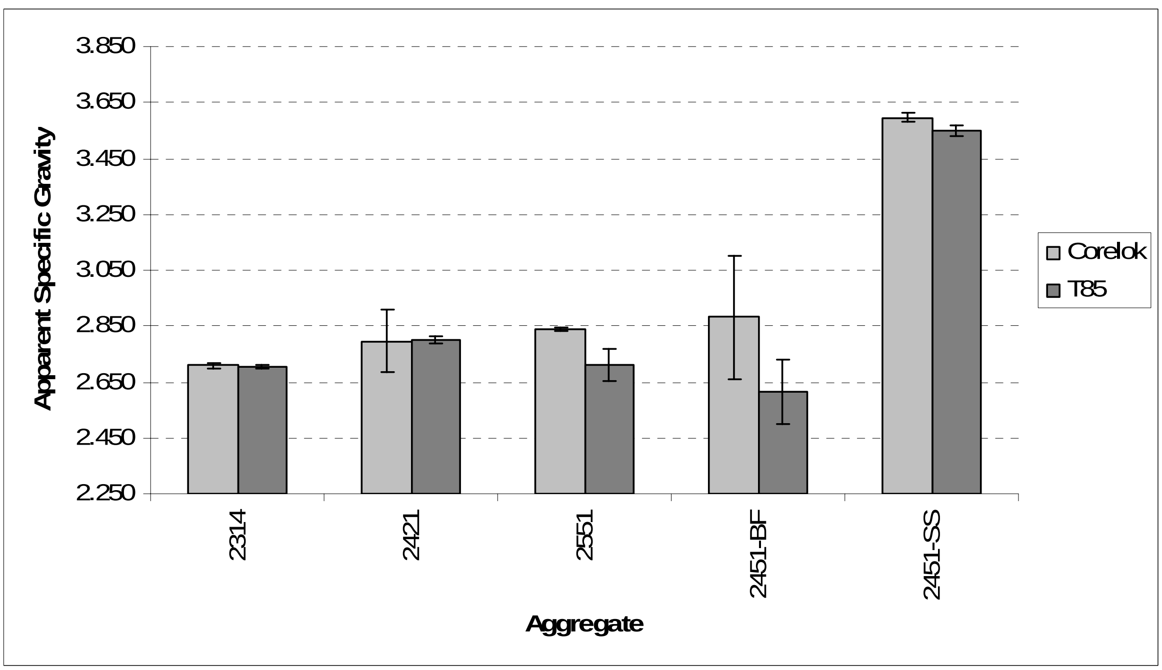

Figure 49. Coarse Aggregate Apparent Specific Gravity (Means).

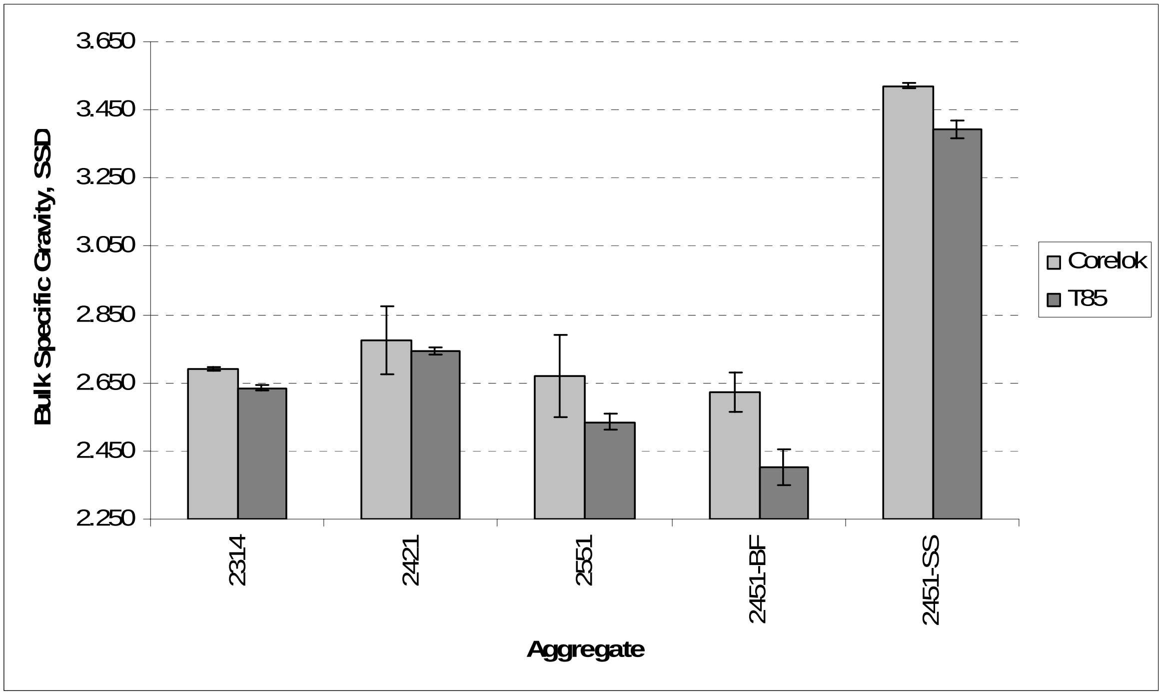

Figure 50. Coarse Aggregate Bulk Specific Gravity, SSD (Means).

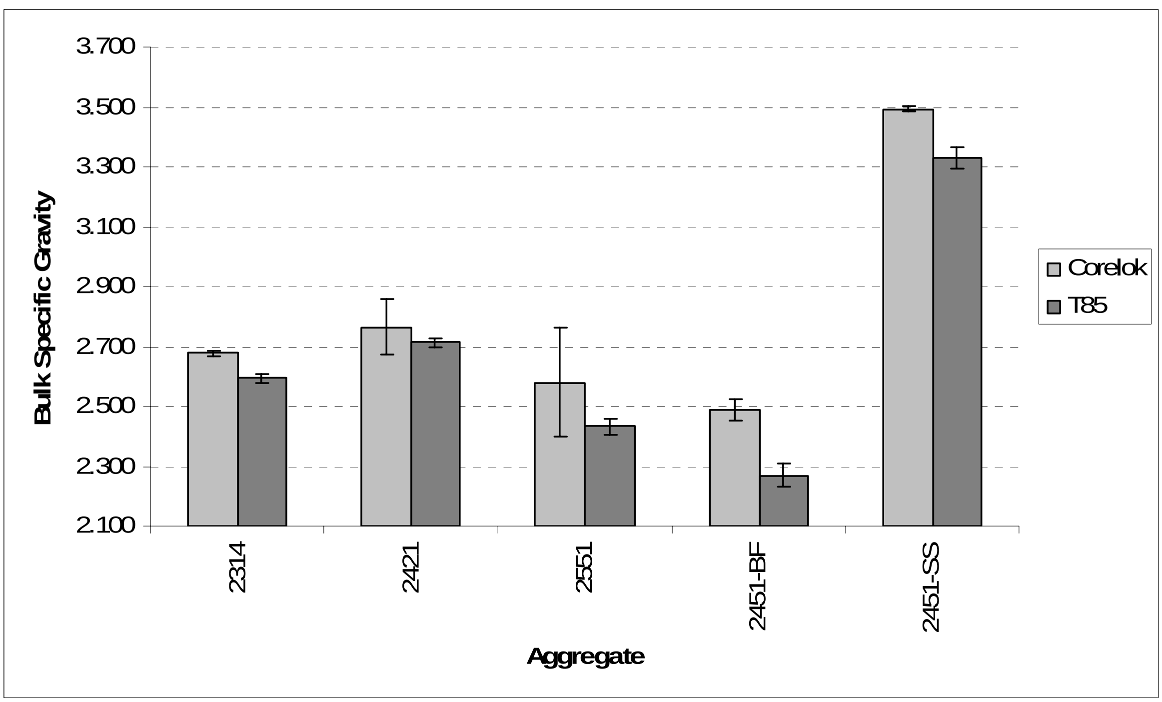

Figure 51. Coarse Aggregate Bulk Specific Gravity (Means).

Testing variation in terms of standard deviation is shown in Figure 52 to Figure 55. Due to the sample degradation during testing, as discussed above, only testing variation obtained from the replicates is comparable to the specification limits and all statements of testing variation refer to the replicate testing. Based on the test results it can be speculated that first testing "cleaned" the aggregate pores of dust and in the subsequent testing water absorption increased due to the easier access of water into the pores, which caused an increase in the bulk specific gravity and water absorption test results.

The two higher absorptive aggregates, CA # 2551 Dolostone and CA # 2451 blast furnace slag, had more testing variation than the other aggregates in percent absorption and bulk specific gravity. Also, the steel slag CA # 2541 had increased testing variation compared to the stone aggregates.

The testing variation of the AASHTO T85 tests for stone aggregate was below the (1s) testing limit and testing variation for the highly absorptive aggregates was above the limit. This is an expected result in a sense that it is stated in the T85 precision statement that the limit is applicable only to the aggregate with less than 2% water absorption. Testing variation for slag aggregates was above (1s) limit for all parameters except for apparent specific gravity for steel stag. The Corelok was up to 14 times and overall 6 times above the (1s) AASHTO T85 limit for the water absorption testing and overall 3.4 to 4.9 times above the limit for the specific gravities.

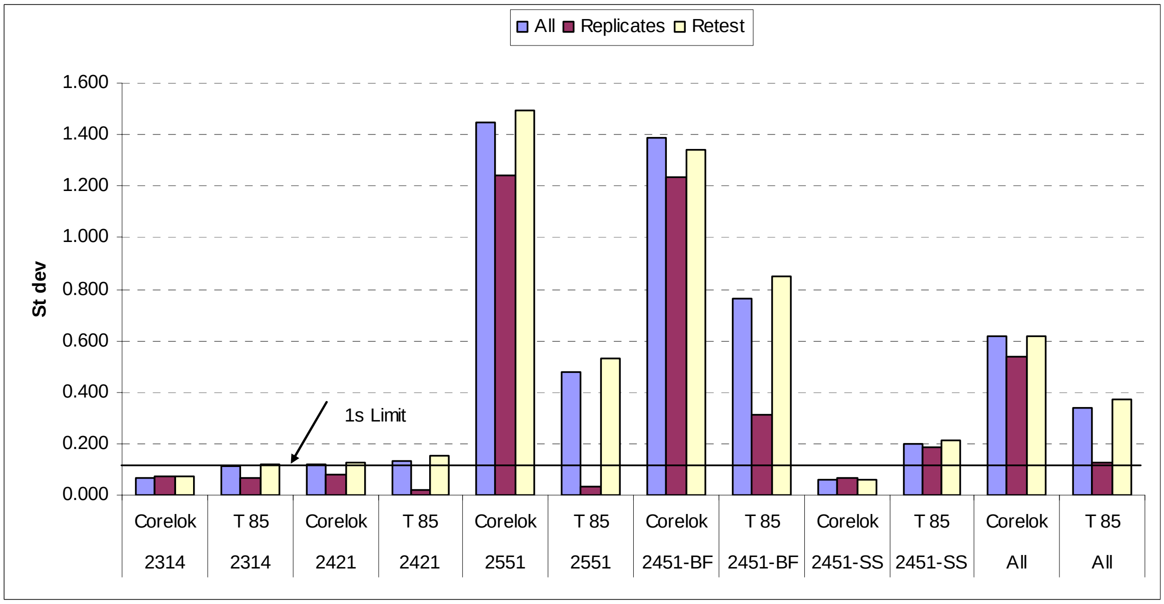

Figure 52. Percent Absorption of Coarse Aggregate.

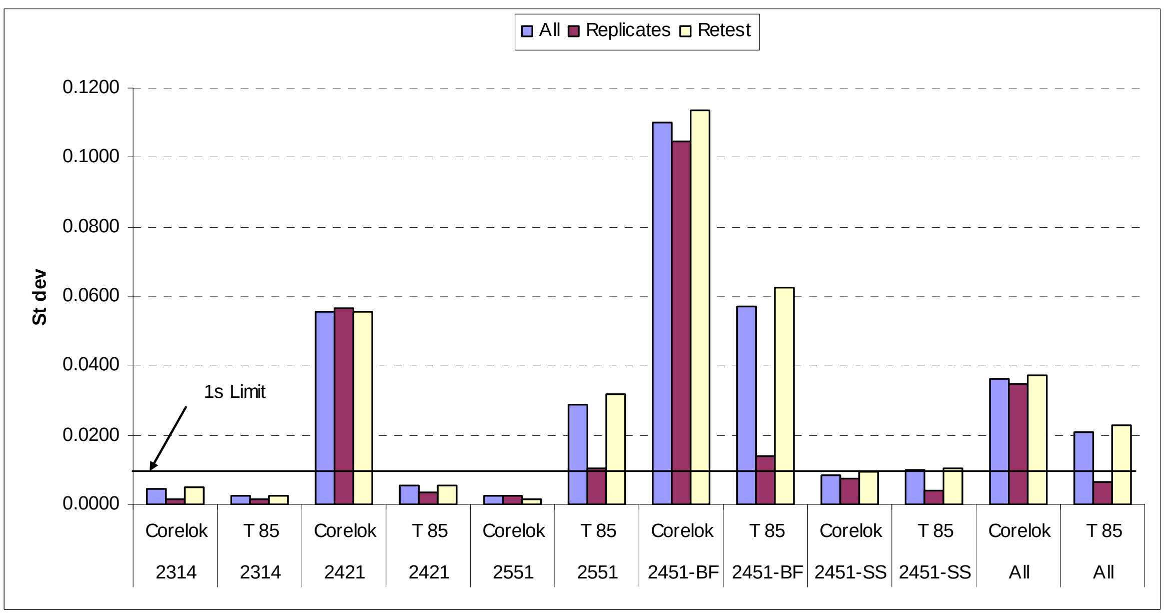

Figure 53. Apparent Specific Gravity of Coarse Aggregate.

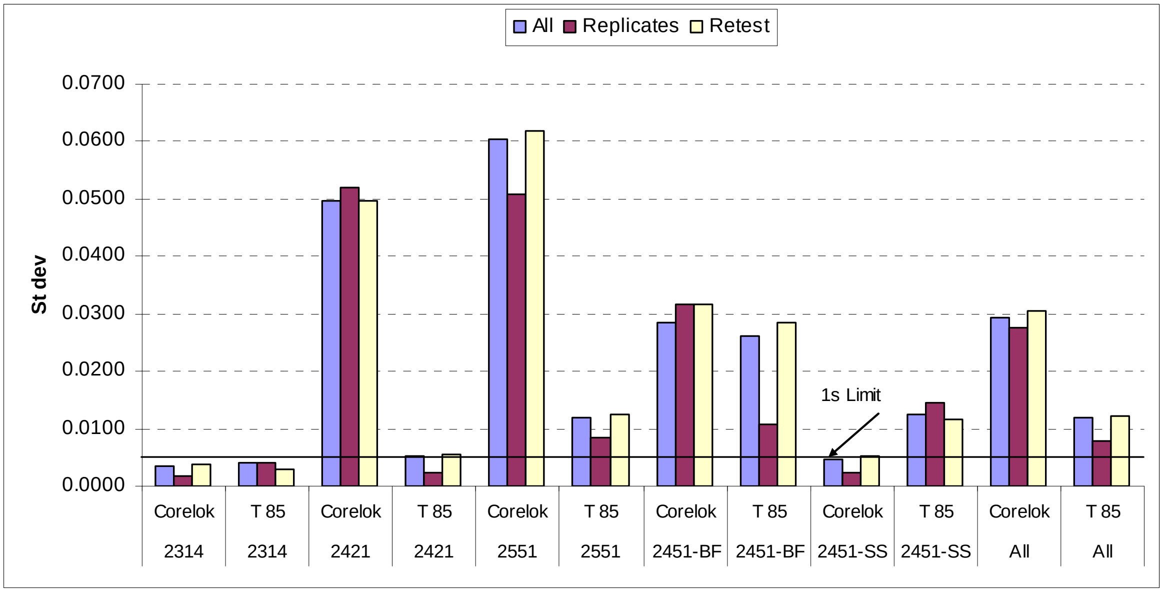

Figure 54. Bulk Specific Gravity, SSD of Coarse Aggregate.

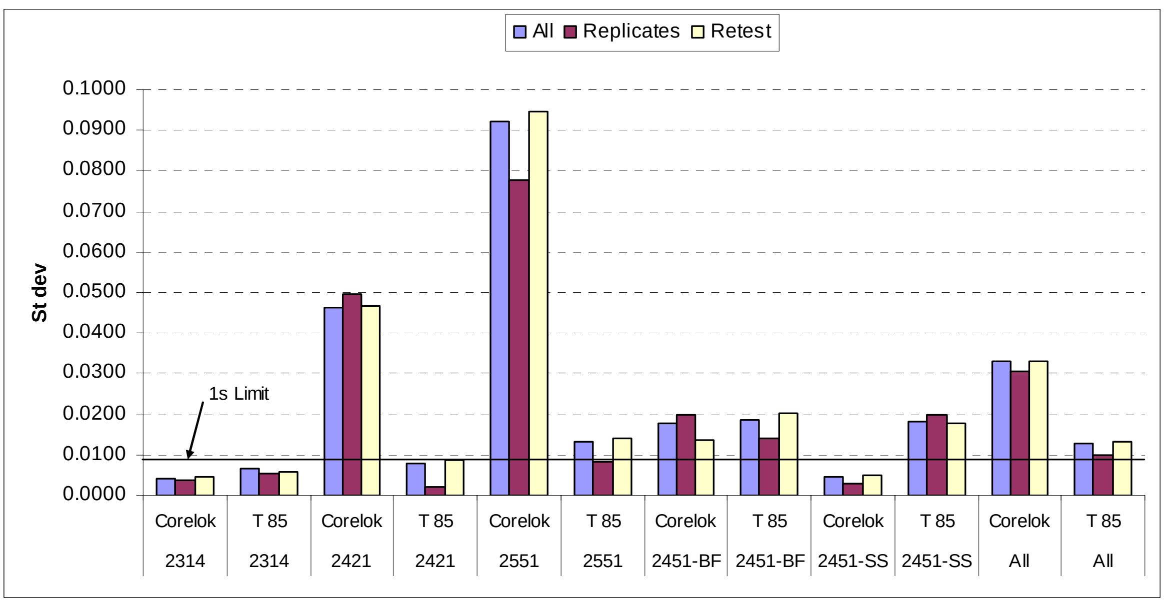

Figure 55. Bulk Specific Gravity of Coarse Aggregate.

6.4.3 Theoretical Maximum Specific Gravity of HMA

The Theoretical Maximum Specific Gravity of HMA data was analyzed similar to the aggregate data described above. The results from this analysis can be found in Table 61. Figure 56 and Figure 61 display the results from the analysis in graphical form.

Additional information including the original test data can be found in Appendix C and F. Table 60 shows that the retesting had slightly lower testing variation compared to the variation of replicate specimens. This is opposite what was found for the aggregate testing and indicates that there is no or very little sample degradation or altering that happens during the retesting of the same specimen. This is an expected result because the binder film coats the aggregates and the cleaning phenomenon that was observed especially for the coarse aggregate does not take place.

Figure 56 to Figure 60 compare the means of the test results for Corelok and T209. Overall, the difference between the measured G_{mm} values was not statistically significantly different. In addition the difference between the means is more or less within the (d2s) multi-laboratory limit for T209.

Table 61. G_{mm} Variation.

			All		First Two Rep.		Replicates	Retests
			Avg	St. Dv	Avg	St. Dv	St. Dv	St. Dv
Mix 1	Corelok	G_{mm}	2.662	0.0097	2.664	0.015	0.0124	0.0036
	T 209	G_{mm}	2.656	0.0068	2.655	0.007	0.0086	0.0048
	T 209	G_{mm} w/ suppl.	2.646	0.0129	2.635	0.016	0.0123	0.0166
Mix 2	Corelok	G_{mm}	2.512	0.0303	2.517	0.054	0.0332	0.0247
	T 209	G_{mm}	2.490	0.0113	2.490	0.015	0.0145	0.0009
	T 209	G_{mm} w/ suppl.	2.477	0.0103	2.479	0.011	0.0129	0.0048
Mix 3	Corelok	G_{mm}	2.543	0.0085	2.553	0.003	0.0039	0.0094
	T 209	G_{mm}	2.525	0.0051	2.522	0.000	0.0055	0.0061
	T 209	G_{mm} w/ suppl.	2.457	0.0053	2.451	0.002	0.0034	0.0063
Mix 4	Corelok	G_{mm}	3.088	0.0058	3.090	0.008	0.0064	0.0049
	T 209	G_{mm}	3.071	0.0047	3.072	0.008	0.0058	0.0040
	T 209	G_{mm} w/ suppl.	3.069	0.0055	3.069	0.010	0.0069	0.0045
ALL	Corelok	G_{mm}	2.701	0.0136	2.706	0.028	0.0139	0.0106
	T 209	G_{mm}	2.686	0.0070	2.685	0.009	0.0086	0.0039
	T 209	G_{mm} w/ suppl.	2.662	0.0085	2.658	0.011	0.0089	0.0081

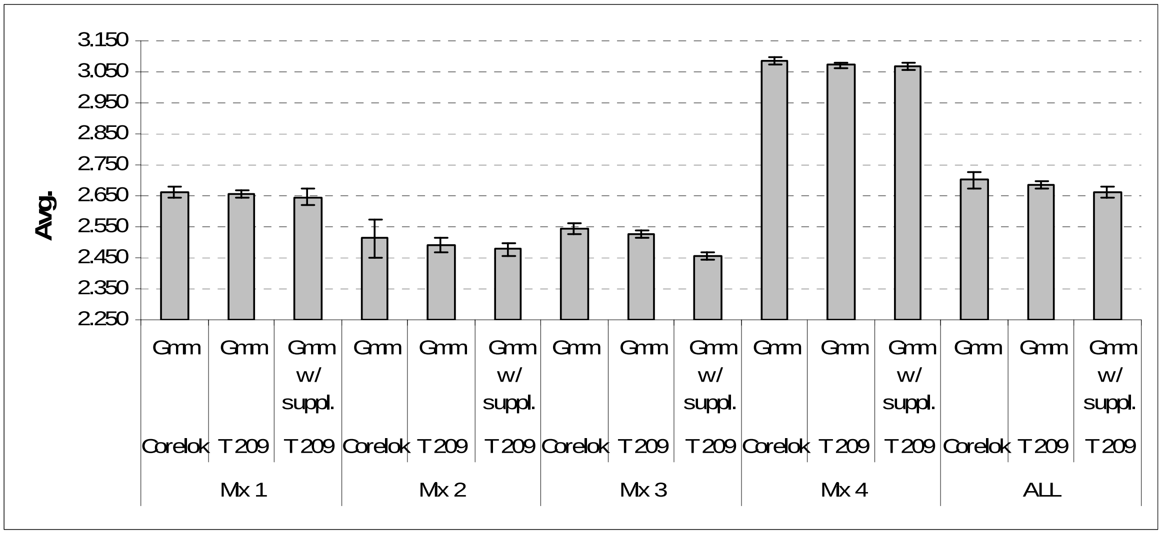

Figure 56. Mix Average G_{mm}.

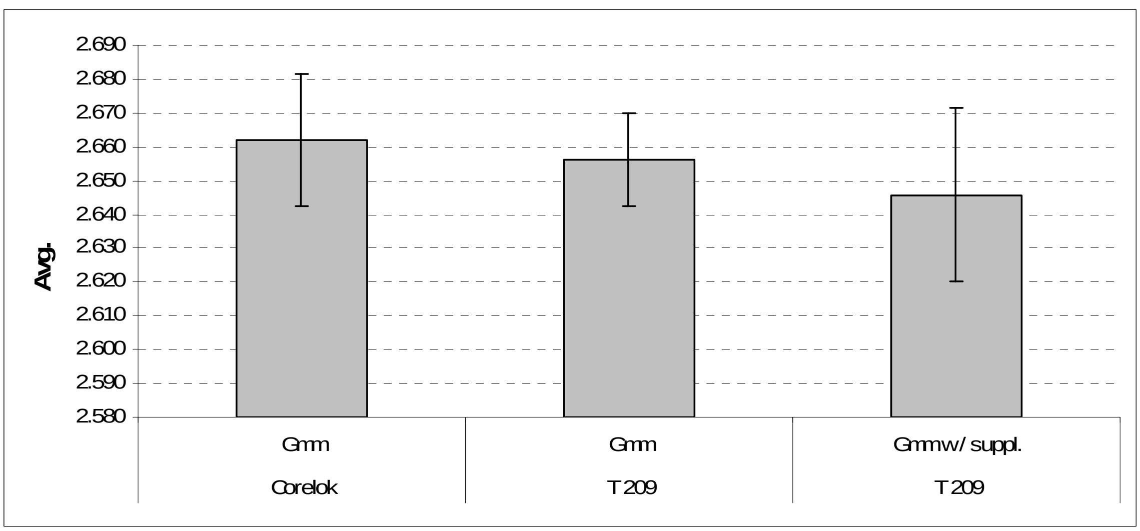

Figure 57. Mix 1 Averages.

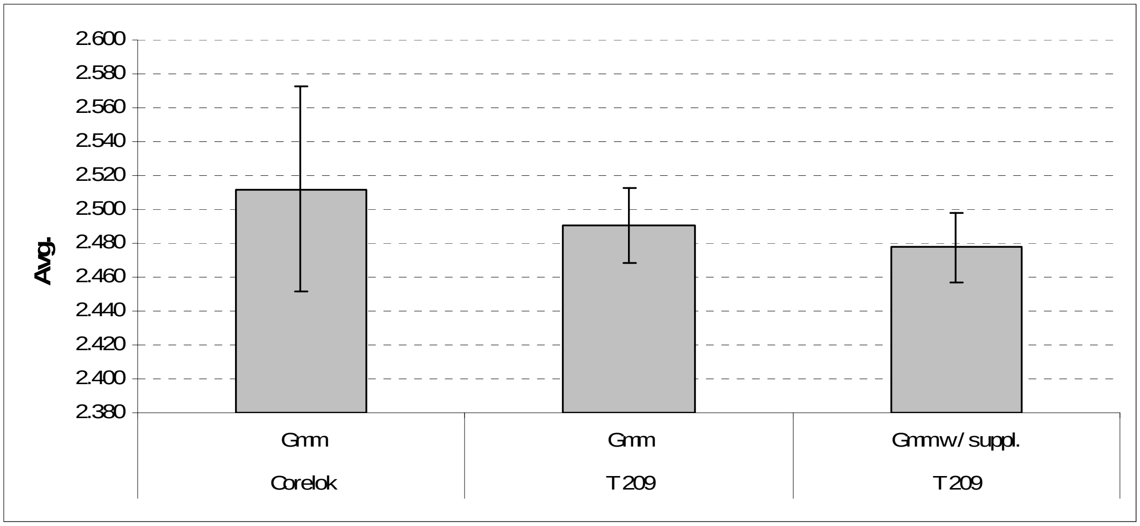

Figure 58. Mix 2 Averages.

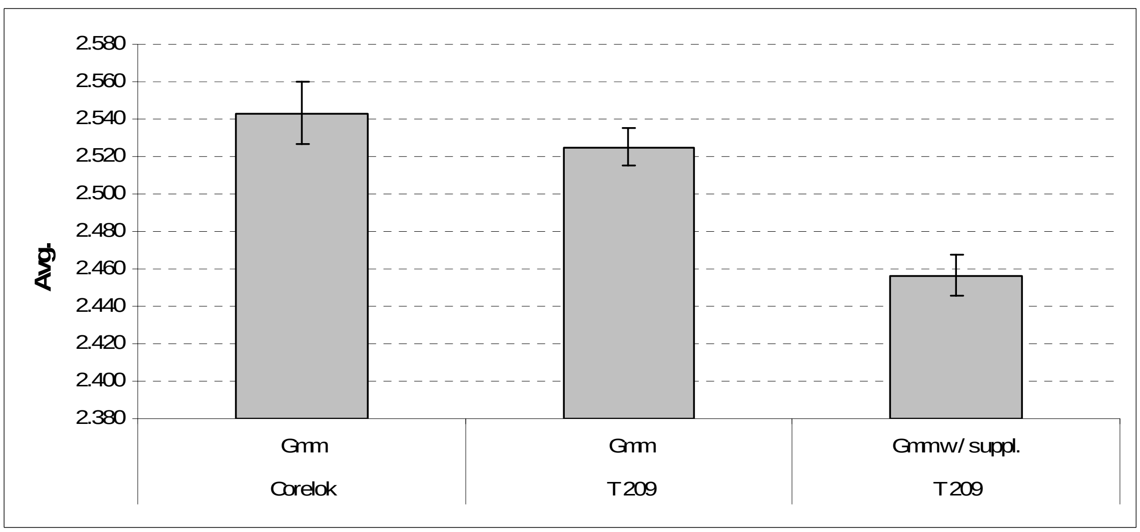

Figure 59. Mix 3 Averages.

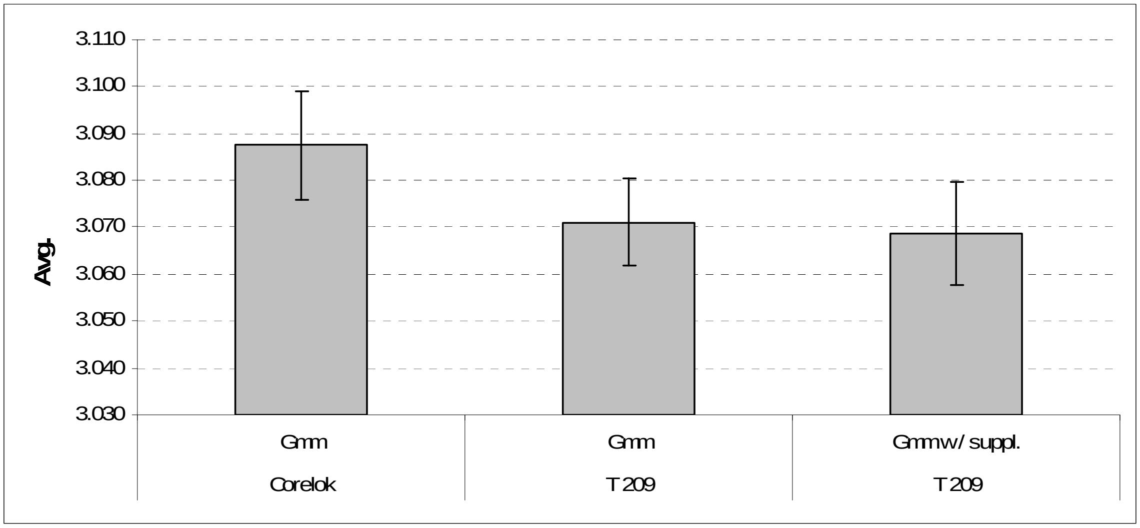

Figure 60. Mix 4 Averages.

Figure 61 shows the testing variation for the G_{mm}. Mixture 2 which used a higher absorptive stone aggregate had a higher overall variation than any of the other mixes. The other high absorptive aggregate mix was Mix 3 with blast furnace slag. However, the testing variation was similar to that of the lower absorptive aggregate mixtures. The overall testing variation of the AASHTO T209 test was at the (1s) limit for both the standard procedure and the supplemental. The overall variation of the Instrotek Corelok was about twice the limit for the standard AASHTO procedure. The supplemental procedure gave systematically lower G_{mm} values except for the mix with steel slag.

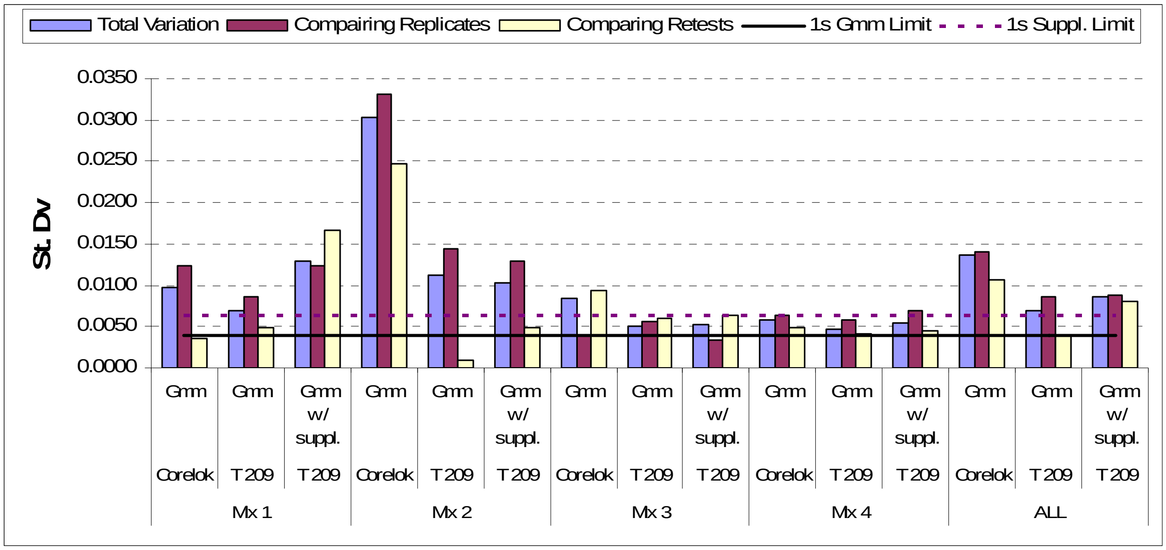

Figure 61. Variation of G_{mm} by Mix.

6.5 Statistical Analysis using ANOVA

The basic statistical analysis was preformed on the data to measure the difference in variation between each of the aggregates and tests. However, the basic statistical analysis could not indicate whether or not the results were statistically significantly different. An advanced statistical analysis for analysis of variance (ANOVA) was preformed using a statistical analysis program STATISTICA.

The analysis of variance is based on the hypothesis testing of the equality of means in the different data sets called groups. A null hypothesis H_0:"equal means in data groups" is tested against an alternative Hypothesis H_A where at least one pair of group means are not equal. The hypothesis is tested using the following test statistics

$$F = \frac{MS_b}{MS_w}$$

in which MS_b and MS_w are mean squares between and within variation, and F is the value of random variable having an F distribution. (McCuen, 1985). The hypothesis testing involves determining the critical value of the test statistics from statistical tables, and comparing computed F value to the critical value. The region of rejection of the null hypothesis H_0 consists of all values of F greater that the critical value. In other words, if the

H_0 is greater than critical F, the null hypothesis should be rejected and alternative hypothesis H_A accepted. This then means that in the compared groups at least one pair did not have equal means.

The level of significance, α, incorporates the concept of risk for the decision making in the hypothesis testing and it represents the probability of making type I error. Type I error is made when H_0 is rejected when, in fact, H_0 is true. The level of significance should not be made exceptionally small, because the probability of making type II error increases. Type II error is made when H_0 is accepted when, in fact, it is false.

ANOVA results were evaluated at the level of significance α of 0.050 which gives 5% possibility of making Type I error or 95% certainty of significant difference between the means of aggregates, tests, or level of interaction between the two.

The interaction term gives a way to evaluate the interaction between the different aggregates and the test methods. If there is no interaction, then a single calibration value between the AASHTO test and the Corelok test would exist for every aggregate, because the differences between the methods are additive. If there is significant interaction, then test methods could not be correlated with a single value for all of the aggregates because the differences between the methods are multiplicative.

6.5.1 Analysis of Specific Gravity and Absorption of Fine Aggregates

The advanced analysis was preformed by creating a nested factorial ANOVA. This method compares the means of the AASHTO test results with the results from the Corelok test for each of the test statistics. The sum of the mean squares is computed for each comparison. From these differences an F Statistic is computed for each test group. The F Statistic is then used to determine the significance level for type I error.

The results are shown in Table 62. Based on the results, statistically the percent absorption is the same for both fine aggregates, however T85 and Corelok may give statistically significantly different absorption values depending on the type of aggregate. The same conclusions are valid for the bulk specific gravity. The bulk specific gravity (SSD) results indicate that the two aggregates have different specific gravities, and the difference is test method dependent. The apparent specific gravity results indicate that the two aggregates have different apparent specific gravities, and both test methods measure the same order for the aggregates, i.e. there is no interaction between the tests and aggregate types.

Table 62. Advanced Statistical Analysis of Fine Aggregates.

	Test Groups	F Statistic	Significant Difference in Group Means	Interpretation
Percent Abs.	1. Among Aggregates	2.045	No	Aggregates have same Abs.
	2. Among Tests	187.016	Yes	T84 and CL give different Abs.
	3. Interaction	285.486	Yes	T84 and CL results depend on agg
Gsb	1. Among Aggregates	13.667	No	Aggregates have same Gsb.
	2. Among Tests	385.093	Yes	T84 and CL give different Gsb.
	3. Interaction	329.193	Yes	T84 and CL results depend on aggregate
Gsb (SSD)	1. Among Aggregates	30.000	Yes	Aggregates have different Gsb(SSD).
	2. Among Tests	310.345	Yes	T84 and CL give different Gsb (SSD).
	3. Interaction	206.897	Yes	T84 and CL results depend on aggregate
Gsa	1. Among Aggregates	739.130	Yes	Aggregates have different Gsa.
	2. Among Tests	37.037	Yes	T84 and CL give different Gsa.
	3. Interaction	5.291	No	T84 and CL results don't depend on aggregate

T84 is AASHTO T84, CL is Corelok

6.5.2 Analysis of Specific Gravity and Absorption of Coarse Aggregates

The advanced analysis was preformed by creating a nested factorial ANOVA. This method compares the means of the AASHTO test results with the results from the Corelok test for each of the test statistics. The sum of the mean squares is computed for each comparison. From these differences an F Statistic is computed for each test group. The F Statistic is then used to determine the significance level.

The results are shown in Table 63. The percent absorption results indicate that the five different aggregates have different absorptive values, and systematically T85 and Corelok measurement differ for the aggregates. Figure 42 shows that T85 systematically measured higher values than the Corelok. The all specific gravity results indicate that some of the aggregates (2451-SS) have statistically different specific gravity compared to the other aggregates, see Figure 45, and that both test methods report a different result, which depends on type of aggregate tested.

Table 63. Advanced Statistical Analysis of Coarse Aggregates.

	Test Groups	F Statistic	Significant Difference in Group Means	Interpretation
Percent Abs.	1. Among Aggregates	160.550	Yes	Aggregates have different Abs.
	2. Among Tests	19.446	Yes	T85 and CL give different Abs.
	3. Interaction	0.569	No	T85 and CL results do not depend on agg
Gsb	1. Among Aggregates	2159.778	Yes	Aggregates have different Gsb.
	2. Among Tests	238.818	Yes	T85 and CL give different Gsb.
	3. Interaction	11.727	Yes	T85 and CL results depend on aggregate
Gsb (SSD)	1. Among Aggregates	3442.400	Yes	Aggregates have different Gsb(SSD).
	2. Among Tests	281.286	Yes	T85 and CL give different Gsb (SSD).
	3. Interaction	24.000	Yes	T85 and CL results depend on aggregate
Gsa	1. Among Aggregates	1785.222	Yes	Aggregates have different Gsa.
	2. Among Tests	69.353	Yes	T85 and CL give different Gsa.
	3. Interaction	22.000	Yes	T85 and CL results depend on aggregate

T85 is AASHTO T85, CL is Corelok

6.5.3 Analysis of Theoretical Maximum Density of a Mix

The advanced analysis was preformed by creating a nested factorial ANOVA. This method compares the means of the AASHTO test results with the results from the Corelok test for each of the test statistics. The sum of the mean squares is computed for each comparison. From these differences an F Statistic is computed for each test group. The F Statistic is then used to determine the significance level. The results are shown in Table 64. The theoretical maximum density results indicate that mixtures do not have the same theoretical specific gravity, and that both tests report different results depending on which mix is tested.

Table 64. Advance Statistical Analysis of G_{mm} of a Mix.

	Test Groups	F Statistic	Significant Difference in Group Means	Interpretation
Gmm	1. Among Mixes	1661.9	Yes	Mixtures have different Gmm
	2. Among Tests	93.0	Yes	T209 and CL give different Gmm
	3. Interaction	20.0	Yes	T209 and CL results depend on mixture

T209 is AASHTO T209, CL is Corelok

6.6 Summary of Findings

Precision

The analysis of the fine aggregate testing revealed that the Corelok was a more variable form of testing compared to the AASHTO testing for the percent absorption, bulk specific gravity, and bulk specific gravity (SSD). The AASHTO T84 test results were at or below the (1s) AASHTO limit for all of the measured categories. The Corelok testing variation was above the (1s) limit for all categories except for apparent specific gravity.

The analysis of the coarse aggregate testing revealed that the Corelok was a more variable form of testing compared to the AASHTO testing for the percent absorption, bulk specific gravity, apparent specific gravity and bulk specific gravity (SSD). The AASHTO T85 test results were below the (1s) AASHTO limit for stone aggregates which had water absorption below 2%. For stone aggregate and blast furnace slag which had water absorption between 4 and 5% the testing variation exceeded the AASHTO (1s) limit. The Corelok testing variation exceeded the AASHTO limits up to 14 times being overall 3 to 4 times higher. In addition, Corelok had higher testing variation for the aggregate with high water absorption.

The analysis of the theoretical maximum specific gravity of HMA indicated that the standard AASHTO T209 procedure had a smaller variation than the supplemental procedure and the Corelok testing procedure. Both standard and supplemental procedures were below or at the AASHTO (1s) limit. The Corelok method exceeded the AASHTO (1s) limit for both standard and supplemental tests. The supplemental procedure gave systematically lower G_{mm} values compared to the standard procedure except for mix with steel slag.

Bias

Analysis showed that for the fine aggregate the Corelok testing gave lower water absorption and higher specific gravity values than the T84. However differences between the means were below the multi-laboratory (d2s) limit. Therefore, the bias may not be considered substantial between these two test methods. However, the there were more variation in the manufactured sand test results compared to the natural sand.

The coarse aggregate analysis showed similar results for the Corelok test method as compared to the AASHTO standard of T85. However, now the average test results were above the multi-laboratory (d2s) limits. Therefore, it is not recommended that these test methods be used interchangeably.

The theoretical maximum specific gravity analysis showed that Corelok systematically gave higher specific gravity values compared to standard T209 method. However, the difference was overall within the multi-laboratory limit of (d2s).

7 ANALYSIS OF EXISTING PCC DATA TO QUANTIFY VARIABILITY

This chapter describes the analysis of several different databases of concrete material test results for the specific purpose of quantifying the variability associated with testing procedures used by INDOT for determining portland cement concrete (PCC) properties. The data was analyzed to determine two main sources of variability in terms of:

- the inherent material, sampling, and testing variability (S_S+S_{TE}) and
- the inherent material, sampling, testing variability, as well as variability associated with production which will be referred to as total variability (S_T).

The analysis performed in this study considered several material and construction acceptance properties associated with portland cement concrete. The primary tests that were investigated included the material tests and properties associated with acceptance in concrete pavements including: plastic air content, flexural strength, and pavement thickness. In addition, compressive strength was analyzed due to its use in the acceptance of superstructure concrete and split tensile strength was analyzed due to its use in the appeal process for pavement strength. Other tests that were analyzed include unit weight, aggregate specific gravity and aggregate absorption due to their importance in controlling the production process. A total of eleven sources of data were statistically analyzed for assessing the variability associated with concrete construction. Each source of data is described in greater depth in section 7.2.

7.1 A Review of Procedures for Obtaining a PCC Sample (AASHTO T141)

The scope of this report consisted of an analysis of data that was provided to the Purdue-INDOT research team. During this analysis it has been assumed that the concrete was sampled in accordance with the procedures described in AASHTO T141 "*Sampling Freshly Mixed Concrete*". The scope of this sampling procedure is to describe the appropriate process which is to be used for obtaining representative samples of fresh concrete from a variety of sources including sampling from stationary, paving, and truck mixers, as well as sampling from agitating and non-agitating equipment used to transport central mixed concrete. The following excerpts have been paraphrased from the AASHTO

T141 standard to clarify the sampling procedures that have been assumed to have been performed in collecting the data that was used in this study.

Sampling

The elapsed time between obtaining the first and final portions of the composite samples shall be as short as possible, but in no instance shall it exceed 15 minutes.

The individual samples shall be transported to the location where fresh concrete tests are to be performed or where the test specimens are to be molded. They shall then be combined and remixed with a shovel to form at least the minimum amount necessary to ensure uniformity and compliance with the minimum time limits specified in the following section.

Tests for slump, temperature, and air content, shall be started within five minutes after obtaining the final portion of the composite sample. These tests shall be completed as expeditiously as possible. Specimens for strength tests shall be molded within 15 minutes after fabricating the composite sample. The elapsed time between obtaining and using the sample shall be as short as possible. The sample shall be protected from the sun, wind, and other sources of rapid evaporation, and from contamination.

Size of Sample

The samples that are to be used for strength tests shall be taken from a sample with a minimum size of 28 liters (1 ft^3). Smaller samples may be permitted for routine air content and slump tests and the size shall be dictated by the maximum aggregate size.

Sampling from Stationary Mixers, Except Paving Mixers

The concrete shall be sampled by collecting two or more portions taken at regularly spaced intervals during discharge of the middle of the batch. These portions shall be obtained from within the time limit specified above. The sample portions shall be combined into one composite sample for testing purposes. Portions of the composite sample should not be taken from the very first or last part of the batch discharge.

Sampling shall be performed by passing a receptacle completely through the discharge stream, or by completely diverting the discharge into a sample container. If discharge of the concrete is too rapid to divert the complete discharge stream, discharge the concrete into a container or transportation unit sufficiently large to accommodate the entire batch and then accomplish the sampling in the same manner as given above. Care shall be taken to not restrict the flow of concrete from the mixer, container, or transportation unit so as to cause segregation. These requirements apply to both tilting and non-tilting mixers.

Sampling from Paving Mixers

The concrete shall be sampled after the contents of the paving mixer have been discharged. Samples shall be obtained from at least five different portions of the pile and *then composite into one sample for test purposes. Care shall be taken to avoid contamination with subgrade material or prolonged contact with an absorptive subgrade. To preclude contamination or absorption by the subgrade, sample the concrete by placing three shallow containers on the subgrade and discharging the concrete across the containers. The samples shall be combined into a composite as one sample for test purposes. The containers shall be of a size sufficient to provide a composite sample size that is in agreement with the maximum aggregate size.*

7.2 A Description of the Data Sources Used for the PCC Analysis

Several sources of data were provided by INDOT personnel and several contractors in Indiana for this study. A summary of the data sources used is presented in Table 65 while Table 66 describes both the test procedure that was used, the number of replicate specimens in each data source, and the analysis approach.

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Table 65. Summary of Test Data Sources.

Data Source	Name of Testing	Sampling Location
I	INDOT Independent Assurance Testing Program	Field mixtures from various projects
II	Individual Project Sampling for QC Testing	Field mixtures from various projects
III	Individual Project Sampling for QA Testing	Field mixtures from various projects
IV	INDOT PRS Development Testing	Field mixtures
V	Investigation of Critical Quality Assurance Parameter Variations for Concrete	Laboratory mixtures
VI	INDOT Superstructure Study	Laboratory tests**
VII	INDOT Sample Exchange Program	Laboratory mixtures and tests
VIII	INDOT Superstructure Data	Field mixtures from various projects
IX	INDOT Sample Exchange Program and QC/QA	Laboratory tests
X	INDOT Laboratory Testing	Laboratory tests

*Note: Data Source II and III contain some of the same data.

** Note: Tests were performed by INDOT Materials and Tests

Table 66. Summary of Testing Conditions

Data Source	Test Method	Parameter	Testing Agency	Replicate Tests	No of Technicians	No of Labs	Testing Conditions**		Production Variability
							Operator	Machine	
I	AASHTO T152 / ASTM C173	Air Content (%)	State	2	2	1	Multi	Multi	No
II	AASHTO T152 / ASTM C173	Air Content (%)	Contractor	1 per batch	1	1	Single	Single	Yes
	AASHTO 121	Unit Weight (lbs/yd^3)	Contractor	1 per batch	1	1	Single	Single	Yes
	AASHTO 97	Flexural Strength (psi)	Contractor	2 per batch	1	1	Single	Single	Yes/No*
III	AASHTO T152 / ASTM C173	Air Content (%)	Contractor /State	1 per batch	1 C/S	2	Single/Multi*	Single/Multi*	Yes/No*
	AASHTO 121	Unit Weight (lbs/yd^3)	Contractor /State	1 per batch	1 C/S	2	Single/Multi*	Single/Multi*	Yes/No*
	AASHTO 97	Flexural Strength (psi)	Contractor /State	2 per batch	1 C/S	2	Single/Multi*	Single/Multi*	Yes/No*
IV	AASHTO 97	Flexural Strength (psi)	State	2 per batch/sublot	1	1	Single	Single	Yes
	ITM 404	Thickness (in)	State	1 per batch/sublot	1	1	Single	Single	Yes
V	AASHTO 97	Flexural Strength (psi)	State	3 per batch	3	1	Multi/Single*	Single	Yes/No*
	ASTM C39	Compressive strength (psi)	State	2 per batch	3	1	Multi/Single*	Single	Yes/No*
	ASTM C496	Split Tensile Strength (psi)	State	2 per batch	3	1	Multi/Single*	Single	Yes/No*
VI	AASHTO T 84/85	Specific Gravity and Absorption	State	1	1	1	Single	Single	No

*Test Condition/Variability is dependent on how the analysis was preformed. **All testing conditions are assumed based upon information provided

Table 65. Con't.

Data Source	Test Method	Parameter	Testing Agency	Replicate Tests	No of Technicians	No of Labs	Testing Conditions**		Production Variability
							Operator	Machine	
VII	ASTM C39	Compressive strength (psi)	State	3	1	1	Multi/Single*	Single	No
VIII	ASTM C39	Compressive strength (psi)	State	2	1	1	Multi/Single*	Single	Yes
	AASHTO T152 / ASTM C173	Air Content (%)	State	1	1	1	Multi	Single	Yes
IX	AASHTO T84/85	Specific Gravity and Absorption	State	1	1	1	Multi	Single	No
X	ITM 404	Thickness (in)	State	1	1	1	Multi/Single*	Single	Yes

Data Source I

Data source I consisted of data from the INDOT Independent Assurance Testing Program. Data source I included 195 pairs of fresh concrete plastic air content test results that were obtained from various samples throughout the state of Indiana. This data consists of a range of materials and mixture proportions that are consistent with those used for the PCC pavement and superstructure construction. Each sample pair was obtained from the same batch of concrete. This sample was then tested in a side by side format by two INDOT technicians each using a separate apparatus. While the data source consisted of results from plastic air tests, it does not delineate which of the two possible standard test procedures were used in obtaining the data (AASHTO T152 – Standard Method of Test for Air Content of Freshly Mixed Concrete by the Pressure Method and AASHTO T196 – Air Content of Freshly Mixed Concrete by the Volumetric Method). Since the actual testing procedure that was used was not delineated it was assumed for the sake of analysis that only one testing procedure was used and a distinction is not made between these tests. It should be noted that AASHTO T196 has greater acceptable precision limit than AASHTO T152. In addition, AASHTO T152 is used more widely in Indiana and AASHTO T196 is generally only used for high porosity aggregates. As a result, for the sake of the analysis in this report, the pooled variation was compared to the AASHTO T152 testing limits.

Data Source II

Data source II consisted of data that was obtained from three different PCCP construction projects in the state of Indiana (projects R-23900, R-23901, and R-24735). This data was obtained from one contractor from their quality control tests using similar concrete mixture proportions and materials. The test data included one fresh concrete plastic air content test, one fresh concrete unit weight test and two 7-day flexural strength tests (note two beam breaks typically constitute one sample). Plastic air content, plastic unit weight, and flexural strength tests were performed in accordance to AASHTO T152, AASHTO T121 and AASHTO T97 test procedures, respectively. It should be noted that it was assumed, based on discussion with the contractor, that in each project the testing was performed by the contractor using a single technician and single testing apparatus in a mobile testing laboratory. It should however be noted that the technician and mobile testing laboratory was not the same from project to project. Since two flexural strength tests were reported from the same fresh concrete sample the variability associated with the inherent material, sampling and testing (single-operator and single-machine) could be determined by calculating the standard deviation of each pair of flexural strength test results.

Data Source III

Data source III included data from four different PCCP construction projects in Indiana (R-23900, R-23901, R-22855, and R-23804). It should be mentioned that while two of the projects are included in both data source II and III, the data used in source III contained some data that was reported in data source II along with new data. Data source III consists of 348 pairs of plastic air content, plastic unit weight and flexural strength tests (the flexural strength results presented here consist of an average of two individual beam breaks). The data was obtained from a pair of tests that were performed by an INDOT inspector and a contractor's technician during quality assurance testing. Each pair of tests consisted of a fresh concrete plastic air content test, unit weight test and an average flexural strength test (the average of two flexural beams). For the sake of this analysis it was assumed that testing was conducted by the contractor using a single technician and test equipment and testing by INDOT was performed using a single technician and test equipment. The data in this series was obtained using AASHTO T152, AASHTO T121, and AASHTO T97. Since two tests were performed on each sample at the same location the inherent material, sampling, and testing variability could be determined from each pair of test results and the total variability (which includes production variability) could be determined throughout the course of the project.

Data Source IV

Data source IV included 54 flexural strength tests (the average of two beam breaks) and 54 thickness test results obtained from a single PCC pavement contract by a state technician. Two flexural strength tests were performed for each sublot and yielded a single result. Two standard methods were used in obtaining this data which include ITM 404 and AASHTO T97.

Data Source V

Data source V included test data from the laboratory concrete mixtures studied in the "*Investigation of Critical Quality Assurance Parameter Variations for Concrete*". The test methods described in that report included flexural strength, compressive strength, and split tensile strength. Four mixture designs were prepared in that study: 1) crushed stone without fly ash, 2) crushed stone with 10% fly ash, 3) gravel without fly ash, and 4) gravel with 10% fly ash. Overall, eight types of materials and four air content levels for each material were used in that study. A total of 64 batches of concrete were produced in the INDOT laboratory, 2 batches for each material at each air content level. Seven tests were performed for each batch: three flexural strength tests, two compressive strength tests, and two split tensile strength tests. Three INDOT technicians performed all of the tests. Technician X conducted all the tests for the first 32 batches, technician Y conducted all the tests for the next 16 batches, and technician Z conducted all the tests for the remaining batches. Three different standard test methods were used including AASHTO T97, ASTM C39, and ASTM C496.

Data Source VI

Data source VI included bulk specific gravity (SSD) and absorption data for coarse and fine aggregates. This data was collected from the INDOT superstructure database covering a time period from 2000 to 2002. Coarse aggregate from 24 sources and fine aggregate from 12 sources were included in the study. Tests were performed in accordance with AASHTO T85, 8.2 and AASHTO T84, 6.1.2 which are the test procedures for coarse and fine aggregate. It is assumed that a single operator performed all tests (i.e., they were performed at Materials and Tests) and for each aggregate source the variability due to inherent variation in material properties over time due to mining location and operation could be assessed.

Data Source VII

Data source VII contains compressive strength from INDOT's sample exchange program (SEP, numbers 20, 21, and 22). Samples were created for each round of testing by

INDOT, then six samples were shipped to each district lab and tested. Two methods of testing the 6"x12" cylinders were evaluated with each round of testing (sulfur mortar caps and neoprene pads with steel controllers). It is assumed that all three samples in a single round and single method, either sulfur caps or neoprene pads, were tested by the same operator. It should be noted that the sulfur mortar cap data from Lab 4 in SEP #22 was deleted because the cylinders were not tested properly. Since three tests were preformed on each set of three samples by a single operator the testing plus sampling variation could be assessed.

Data Source VIII

This data set contains 28 day compressive strength and air content results from random acceptance samples obtained from three superstructure projects. Each of the projects contained only one mix design so the samples for each project should contain only minimal production variation. Two replicate compressive strength samples and a single air sample were tested for each sublot by a single operator. The variation between the two replicates indicates the testing plus sampling variation. The overall project variation contains testing, sampling and production variation and applies to a multi-operator limit.

Data Source IX

This data set contains aggregate test data from three different sources. The first set of data is from an INDOT “Fine Aggregate Sample Exchange Program”. This “Fine Aggregate SEP” consisted of four rounds of testing (SEP specimens #37, #38, #41, #42). For each round of testing samples were taken from a single source of sand to obtain a stockpile sample. A sample tube was used to collect sand from around the stockpile. The sample is then divided up by INDOT Materials and Tests Division and a single sample is sent to different district and area labs for testing. Each lab then reports its results to INDOT Materials and Tests Division. The data set generated the multi-operator variation with minimal sampling and testing variation.

The second set of data is from an INDOT “Coarse Aggregate Sample Exchange Program”. This “Coarse Aggregate SEP” consisted of four rounds of testing (SEP specimens #31, #32, #35, #39). For each round of testing, samples were delivered to

INDOT Materials and Tests Division from a local supplier. The material was then dried and broken down into individual particle sizes. The particles were then recombined to exact graduation and weight. The individual samples are sent out to different district and area labs for testing. The data generated the multi-operator variation with minimal sampling and testing variation.

The third set of data contains samples from "FA and CA Jobsite Samples". These samples were obtained from various QC/QA superstructure contracts. Samples were from various sources over a period of four years. Samples were tested using both AASHTO T85, 8.2 and AASHTO T84, 6.1.2 which are the test procedures for coarse and fine aggregate. It is assumed that a single operator performed all tests for each aggregate source. The variability due to inherent variation in material properties over time is present.

Data Source X

This data set was created using testing preformed at INDOT Greenfield District Testing Laboratory. The data set comes from INDOT core thickness testing. These tests were preformed on two sample cores which each had different design thicknesses. These samples where tested by two different operators. Each operator preformed three tests on each sample. The data was used to generate both a single operator testing variation, and a multi-operator total variation.

7.3 Analysis Approach

The analysis approach attempted to assess each of the sources of variability in the data, however due to limited data each of the variability components could not always be determined. The goal of the data analysis was to determine the variability associated with inherent material variability, sampling (S_S+S_{TE}), and the total variability that can be associated with inherent material variability, sampling, testing, and production (S_T). The replicate test results from each data source provide information on the inherent material, sampling and testing variabilities (S_S+S_{TE}). Testing and inherent material variability are usually associated to each other in most testing procedures on fresh concrete properties, such as plastic air content, plastic unit weight and flexural strength, as the tests are not repeated on the same sample. When test methods can be performed multiple times on the same material, for an example, thickness test, testing and material variability could be then separated, however since the majority of the mixtures use similar materials and proportions it is assumed that the inherent variability will not change dramatically from mixture to mixture or sample to sample. As such it was assumed that inherent material, sampling, testing variability were present in multiple tests performed from the same sample, while each of these variabilities was present along with production variability (i.e. total variability (S_T) when samples were compared from batch to batch.

The testing variability is defined for within laboratory single-operator variability for the majority of the test methods unless specifically stated otherwise. The source of variability that was obtained from each analysis was determined based on the manner in which the data source was obtained as described in section 6.2. Statistical analysis was performed using the following steps for all data sets. The analysis was separated by the single-operator (state or contractor) or multi-operator (both state and contractor test results) variation or both based on the manner in which the data source was obtained as described in section 6.2. While the goal of the analysis was to focus on the variability that could be expected from a single-operator this could not be performed for some of the data series due to the manner in which the data was obtained. As a result some data provided permitted only multi-operator variation to be computed. This was true for the case in which combined sampling and testing variation were obtained by comparing replicate test measurements by state and contractor obtained from the same batch.

7.4 Outlier Detection and Elimination

Before any data analysis was performed the data was plotted and cumulative analysis procedures (Day 2002) were used to reveal whether extreme data points existed. If extreme points were discovered they were carefully inspected to insure that the data had been properly entered into the database. If there were noted errors in data entry the error was corrected. If upon further inspection the data was entered correctly, but the point contributed to a significant increase in variation that would not be consistent with a measurement that could be actually obtained in the field, the point was removed. The decision to remove an outlier was made using an engineering judgment based upon the type of test, the average test variation, and the amount of scatter present in the test results. This was done for only 4 data points and was attributed to either reporting error or machine malfunction in the plastic air content testing.

7.5 Variability Associated with Various Test Procedures

7.5.1 Plastic Air Content

Three data sources (source I, II, and III) were used to evaluate the variability in the plastic air content. A description of the manner by which the plastic air content results were obtained is shown in Figure 62. It can be seen that data source I and III could be used to provide information that does not consider production variability while data source II and III provide information on production variability. Results from the analysis can be seen in Table 67 for the total variability and Table 68 describes the inherent material, testing, and sampling variability. Figure 63 provides a graphical representation of all the variability that was observed in the analyzed data sources.

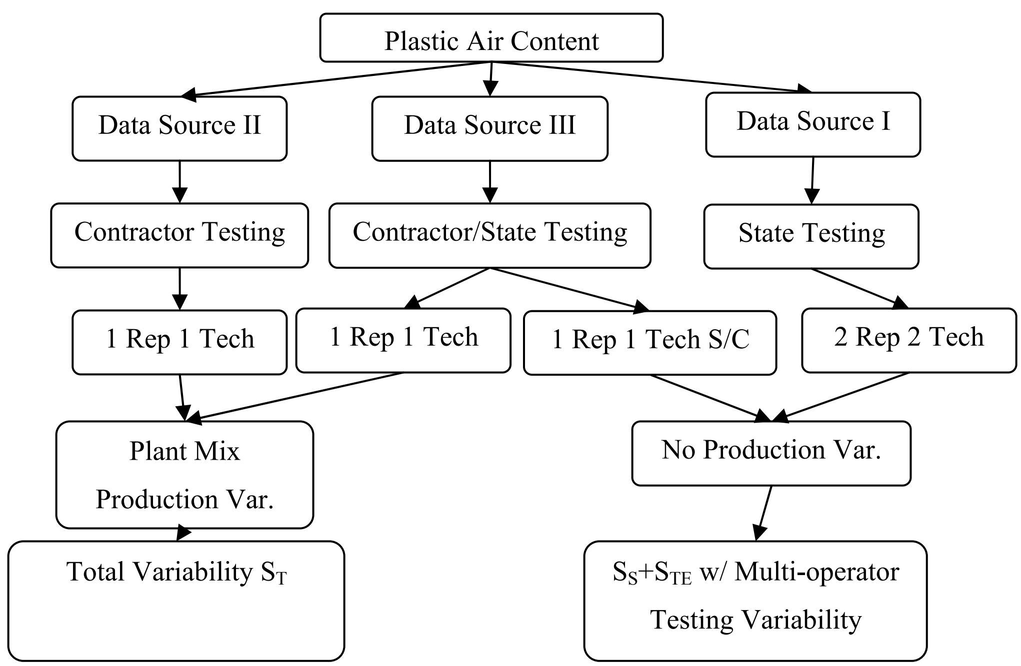


Figure 62. Plastic Air Content Data Flow Chart.

Table 67. Plastic Air Content, % (Total Variability).

Data Source	Project No	n	Total Variability S_T State Avg.	Std. Dev	CV%	Contractor Avg.	Std. Dev	CV%
II	R-23900	64	-	-	-	6.5	0.39	6.0
II	R-23901	77	-	-	-	6.5	0.37	5.7
II	R-24735	83	-	-	-	6.4	0.47	7.2
II	ALL	224	-	-	-	6.5	0.41	6.3
III	R-23900	66	6.4	0.46	7.2	6.5	0.39	6.0
III	R-23901	96	6.4	0.40	5.3	6.5	0.37	5.7
III	R-22855	135	6.5	0.49	7.6	6.5	0.54	8.3
III	R-23804	51	6.6	1.29	19.7	6.4	1.27	19.7

Table 68. Plastic Air Content, % (Isolated Testing Variability).

Data Source	Project No	n	Sampling + Testing Variability (S_S + S_{TE}) w/Multi-operator Testing Variability – State/Contractor Avg.	St. Dev	CV%
I	ALL	195	6.1	0.14*	2.6
II	R-23900	-	-	-	-
II	R-23901	-	-	-	-
II	R-24735	-	-	-	-
II	ALL	-	-	-	-
III	R-23900	132	6.5	0.12	1.9
III	R-23901	192	6.5	0.14	2.2
III	R-22855	270	6.5	0.12	1.9
III	R-23804	102	6.5	0.21	3.3
III	ALL	696	6.5	0.14	2.2

*Tested only by state

It can be seen that the inherent material, testing, and sampling variability was below the (1s) precisions and bias for a multiple operator (0.28) in accordance with Table 16. As a result, Figure 63 shows that the majority of the total variability in terms of standard deviation can be attributed to production variability with the total variability varying from 0.37 to 1.27.

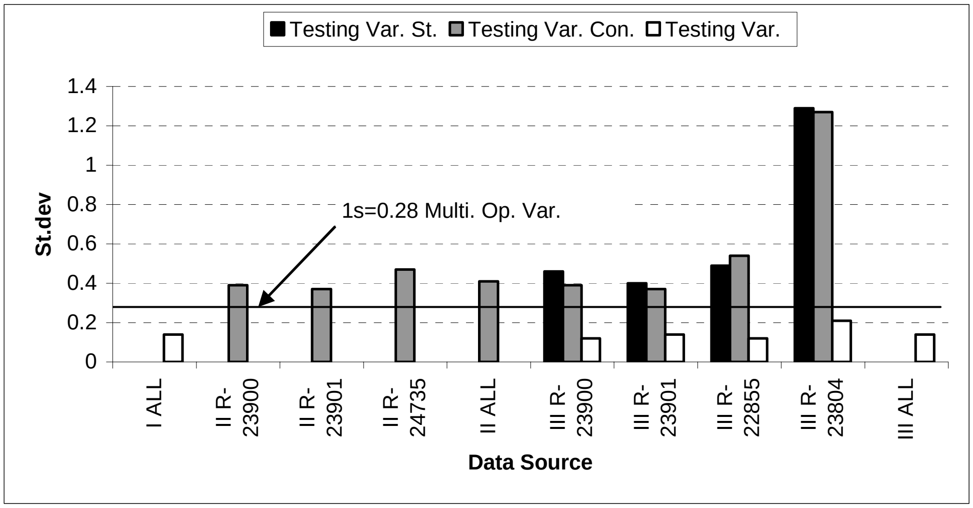


Figure 63. Plastic Air Content.

7.5.2 Plastic Unit Weight

Two data sources (source II, and III) were used to evaluate the variability in the plastic unit weight. A description of the manner by which plastic unit weight results were obtained is illustrated in Figure 64. It can be seen that only data source III could be used to provide information that does not consider production variability. The multi-operator variation was obtained by analyzing differences between the state and contractor data from the same batch using data from source III. Total variability including single-operator testing variability was obtained by analyzing the entire data series for data source II and III. The results of the analysis are displayed in Table 69 and Table 70

Figure 65 provides a graphical representation of all the variability that was observed in the analyzed data sources. The inherent material, testing, and sampling variability was below the (1s) precisions and bias for multi-operator variability (0.82) in accordance with Table 16 and even below the single-operator (1s) limit (0.65) in accordance with Table 15. It should be noted that a single-operator testing variation could not be separated from the production variation. All of the testing variabilities are shown in Figure 65.

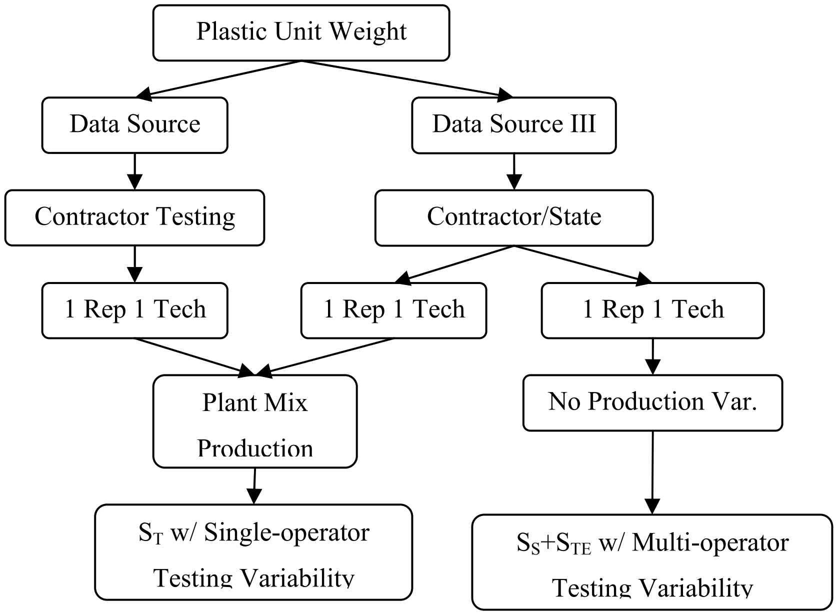


Figure 64. Plastic Unit Weight Data Structure.

Table 69. Plastic Unit Weight, pcf.

			Total Variation S_T w/Single-operator Testing Variability					
			State			Contractor		
Data Source	Project No	n	Avg.	Std. Dev	CV%	Avg.	Std. Dev	CV%
II	R-23900	64	-	-	-	143.4	1.23	0.9
II	R-23901	77	-	-	-	142.7	0.86	0.6
II	R-24735	83	-	-	-	144.2	1.59	1.1
II	ALL	224	-	-	-	143.4	1.22	0.9
III	R-23900	66	144.1	1.13	0.8	143.4	1.24	0.9
III	R-23901	96	143.2	0.86	0.6	142.6	0.93	0.7
III	R-22855	135	145.8	1.43	0.1	145.5	1.03	0.7
III	R-23804	51	144.0	2.16	1.5	143.7	2.20	1.5
III	ALL	-	-	-	-	-	-	-

Table 70. Plastic Unit Weight, pcf.

Data Source	Project No	n	Sampling + Testing Variability ($S_S + S_{TE}$) w/Multi-operator Testing Variability — State/Contractor Avg.	St. Dev	CV%
II	R-23900	-	-	-	-
II	R-23901	-	-	-	-
II	R-24735	-	-	-	-
II	ALL	-	-	-	-
III	R-23900	132	143.7	0.52	0.4
III	R-23901	192	142.9	0.48	0.3
III	R-22855	270	145.7	0.46	0.3
III	R-23804	102	143.9	0.35	0.2
III	ALL	696	144.3	0.46	0.3

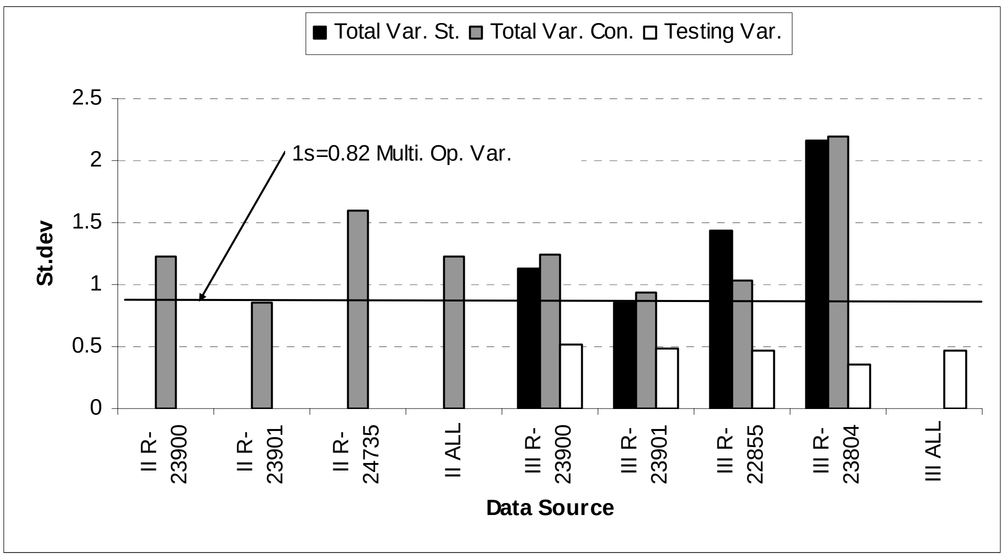


Figure 65. Summary of Plastic Unit Weight Variability.

7.5.3 Flexural Strength

The flexural strength was analyzed using information from data source II, III, IV and V. The description of the manner by which the flexural strength results were analyzed is displayed in Figure 66. The results of the flexural strength analysis are provided in Table 71 for the total variability and in Table 72 for inherent material, testing, and sampling variability. The inter-laboratory single-operator variation was obtained by analyzing the results that were reported for each sample by the state and contractor separately batch by batch (sample by sample) and the multi-laboratory variability was determined by analyzing the state and contractor data from the same batch. It can be noticed that the majority of both the total and inherent material, testing, and sampling variability associated with the flexural strength data falls below the single-operator (1s) limit (5.7%) and multi-laboratory (1s) limit (7.0%) in accordance with Table 15 and Table 17 as shown in Figure 67. The (1s) limit is given in terms of coefficient of variation, see Equation (5).

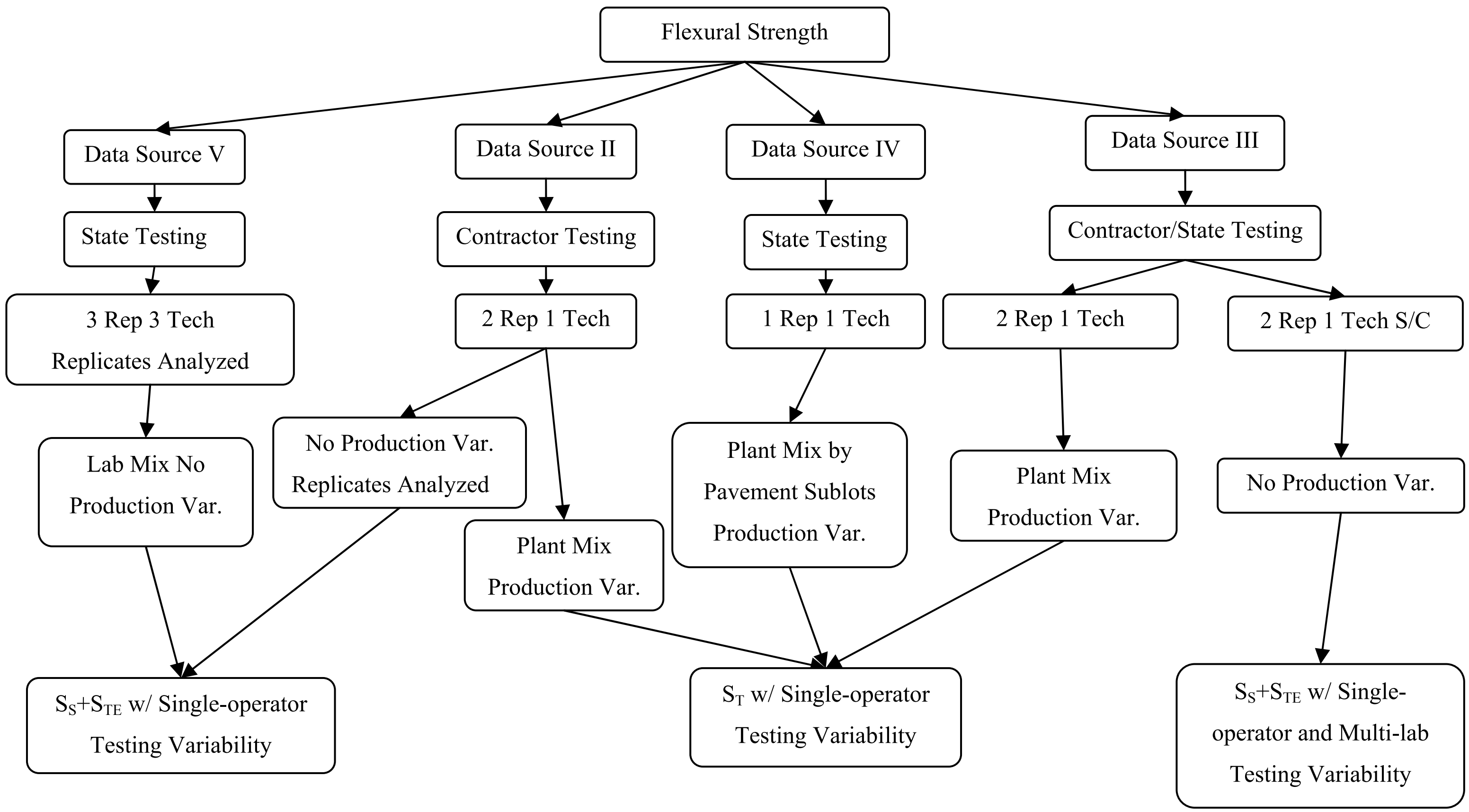


Figure 66. Flexural Strength Data Structure.

Table 71. Flexural Strength, psi.

Data Source	Project No	n	Total Variation S_T w/Single-operator Testing Variability					
			State			Contractor		
			Avg.	Std. Dev	CV%	Avg.	Std. Dev	CV%
II	R-23900	64	-	-	-	724	47.1	7.1
II	R-23901	77	-	-	-	697	42.9	6.8
II	R-24735	83	-	-	-	685	42.4	0.7
II	ALL	224	-	-	-	702	46.5	6.6
III	R-23900	66	735	53	7.2	728	49	6.7
III	R-23901	96	700	43	6.1	700	43	6.2
III	R-22855	135	663	44	6.7	663	47	7.1
III	R-23804	51	656	83	12.6	681	91	13.3
III	ALL	-	-	-	-	-	-	-
IV	ALL	54	682	43	6.2	-	-	-
V	1	-	-	-	-	-	-	-
V	2	-	-	-	-	-	-	-
V	3	-	-	-	-	-	-	-

Table 72. Flexural Strength, psi.

Data Source	Project No	n	Sampling + Testing Variability (S_S + S_{TE}) w/Single-operator and Multi-lab Testing Variability			Single-operator (inter-lab)	Multi-laboratory
			State/Contractor				
			Avg.	Std. Dev	CV%	(1s)	(1s)
II	R-23900	128	724	22.8[a]	3.1	5.7%	
II	R-23901	154	697	18.4[a]	2.6	5.7%	
II	R-24735	166	685	21.0[a]	3.2	5.7%	
II	ALL	448	702	20.6[a]	2.9	5.7%	
III	R-23900	132	733	21.5	2.8		7.0%
III	R-23901	192	699	22.6	3.2		7.0%
III	R-22855	270	663	19.3	2.9		7.0%
III	R-23804	102	661	16.3	2.4		7.0%
III	ALL	696	686	20.2	2.9		7.0%
IV	ALL	-	-	-	-		
V	1	96	676	37[a]	5.2	5.7 %	
V	2	48	650	29[a]	4.4	5.7 %	
V	3	48	690	46[a]	6.5	5.7%	

a)Single-operator variation, results produced from analyzing replicates

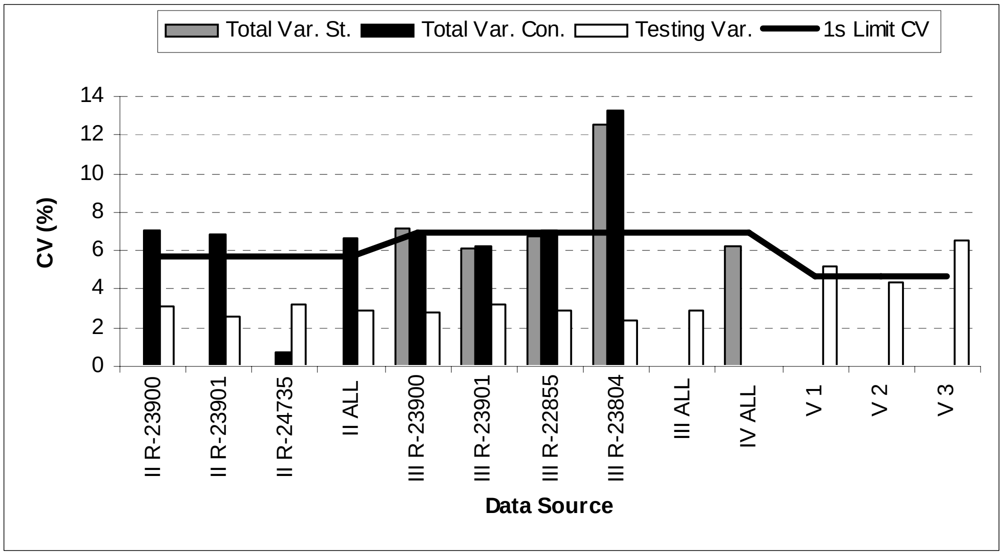


Figure 67. Flexural Strength.

7.5.4 Compressive Strength

The variability from the compressive strength testing was assessed by analyzing the information in data source V. The description of the manner by which the compressive strength results were analyzed is shown in Figure 68, while Table 73 shows the calculated variability by each operator. The variation of the data is shown in Figure 69 along with the allowable coefficient of variation (1s) of 2.37%, according to Table 15, for the test. The inherent material, sampling, and testing variability ($S_S + S_{TE}$) for the compressive strength were generally higher than the allowable limits. Since this analysis was performed using a relatively limited laboratory study additional analysis was performed and results are reported later on in the report.

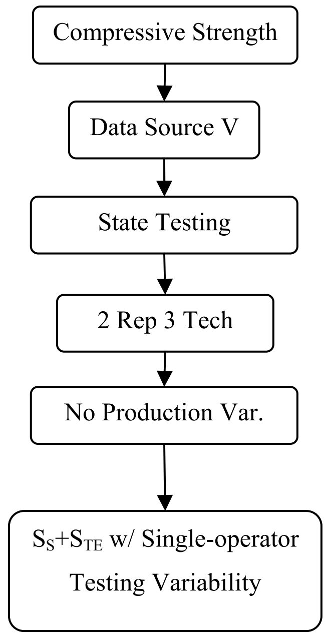


Figure 68. Compressive Strength Data Structure.

Table 73. Compressive Strength, psi.

			Sampling + Testing Variability (S_S + S_{TE}) w/Single-operator Testing Variability		
			State		
Data Source	Operator No	n	Avg.	St. Dev	CV%
V	1	64	4156	161	4.0
V	2	32	4307	145	3.5
V	3	32	3845	129	3.4

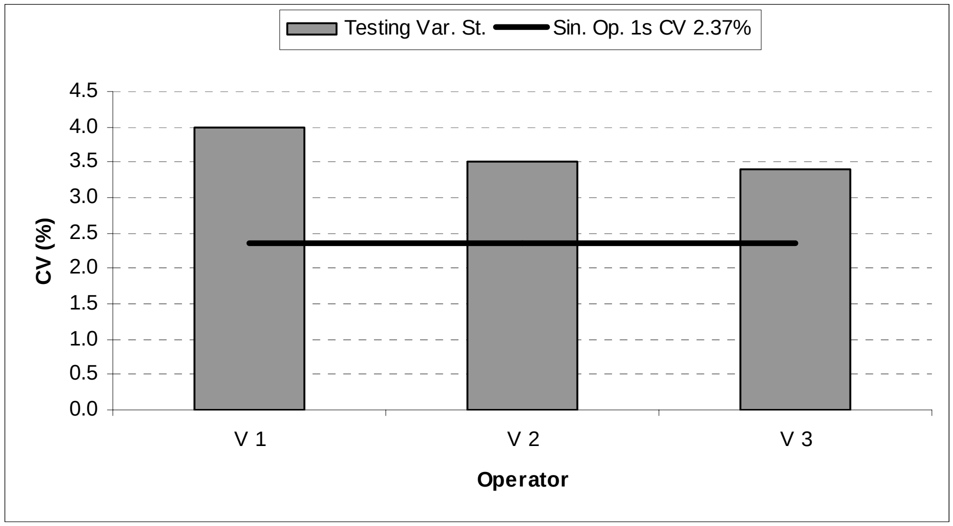


Figure 69. Compressive Strength.

7.5.5 Split Tensile Strength

The split tensile strength was conducted using data set V. The description of the manner by which the split tensile strength results were analyzed is outlined in Figure 70. Table 74 shows the calculated variability by each operator that conducted testing. The single-operator variation was obtained by analyzing the data comparing replicates so that the production variation could be eliminated. The results of the test are shown compared to the (1s) coefficient of variation limit of (5.0%) according to Table 15 in Figure 71.

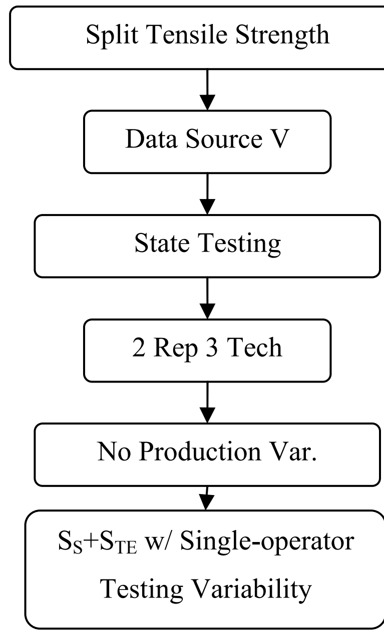


Figure 70. Split Tensile Strength Data Structure.

Table 74. Split Tensile Strength, psi.

			Sampling + Testing Variability (S_S + S_{TE}) w/Single-operator Testing Variability		
			State		
Data Source	Project No	n	Avg.	St. Dev	CV%
V	1	64	521	24	4.5
V	2	32	514	23	4.8
V	3	32	537	29	5.5

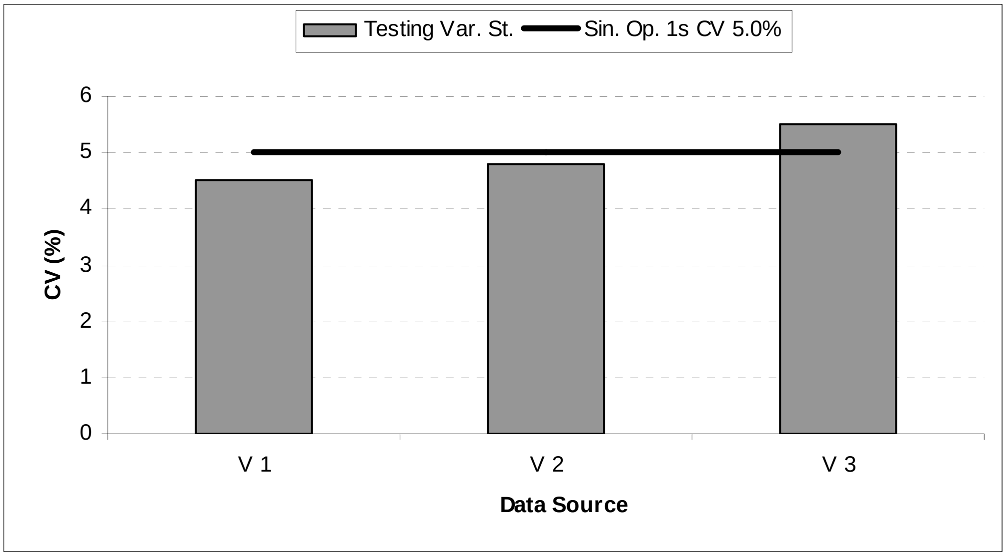


Figure 71. Split Tensile Strength.

7.5.6 Pavement Thickness

The pavement thickness was calculated using data source IV. The data analysis procedure that was used for pavement thickness is shown in Figure 72 while Table 75 shows the calculated total variability for one paving project. The total variability in the measured pavement thickness was relatively low; however there is currently no information on the inherent material, sampling, and testing variability or standard to provide a comparison for the standard deviation. Although the total variability is known, the production variability can not be calculated because no data on the inherent material, sampling, and testing variability exists. Further analysis was performed and results are presented later on in this report.

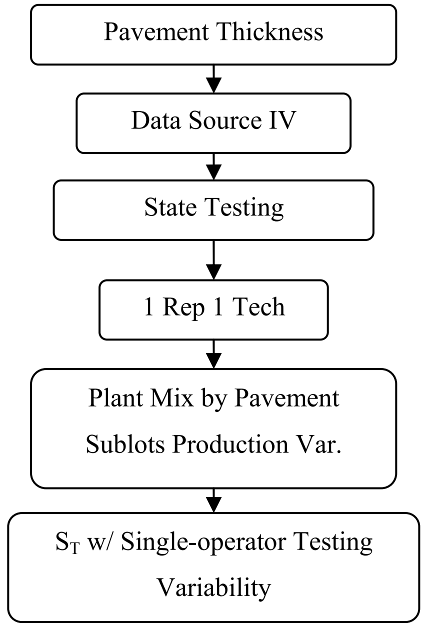


Figure 72. Pavement Thickness Data Structure.

Table 75. Pavement Thickness, in.

			Total Variation S_T w/Single-operator Testing Variability		
			State		
Data Source	Project No	n	Avg.	St. Dev	CV%
IV	ALL	56	14.4	0.31	2.1

7.5.7 Specific Gravity and Absorption of Aggregates

The variability in the surface saturated (SSD) bulk specific gravity and absorption were assessed using data source VI. The description of the manner by which the specific gravity and absorption were analyzed is displayed in Figure 73. The data analysis was conducted using different aggregate sources and comparing the results of one operator within each quarry. Because data did not contain replicate test results testing variability could not be isolated from the total variability (S_T). The results of the analysis are displayed in Table 76 and Table 77, while Figure 74 and Figure 75 provide a graphical representation of the single-operator (1s) variation in comparison to the AASHTO standard, see Table 15. Overall, for fine aggregate the total variability is about two times greater than the variability that is described in the standard for the fine aggregates and about three times greater than that described for the coarse aggregates. It should however be noted that the testing from data source VI was not conducted in a manner that is comparable to the specification since multiple tests were not performed on the same specimen. As such further investigation is needed before a definite conclusion can be reached.

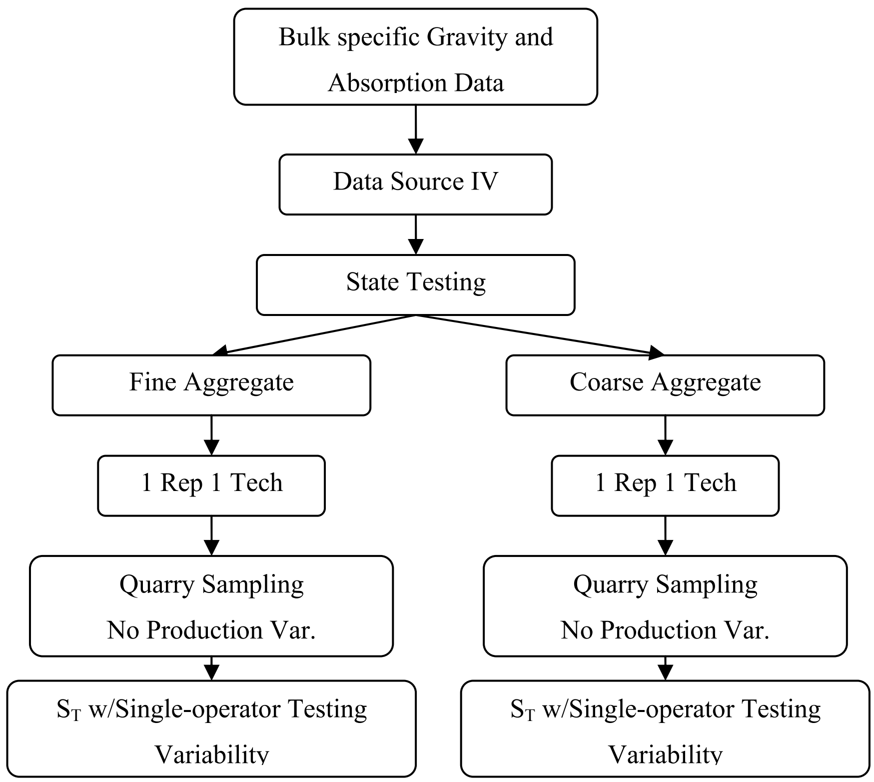


Figure 73. Data Structure of SSD Bulk Specific Gravity and Absorption.

Table 76. Coarse Aggregate SSD Bulk Specific Gravity and Absorption.

		Total Variation S_T w/Single-operator Testing Variability					
		SSD G_{mb}			Absorption (%)		
Source #	n	Avg.	St. dv	CV (%)	Avg.	St. dv	CV (%)
2135	4	2.688	0.0079	0.29	1.08	0.089	8.27
2159	4	2.676	0.0108	0.41	1.38	0.104	7.57
2180	5	2.703	0.0111	0.41	0.75	0.105	14.06
2211	5	2.667	0.0265	0.99	2.78	0.163	5.85
2235	3	2.709	0.0099	0.36	2.37	0.099	4.19
2311	3	2.680	0.0277	1.03	2.18	0.166	7.65
2314	8	2.652	0.0056	0.21	1.45	0.075	5.16
2324	4	2.704	0.0093	0.34	1.87	0.096	5.16
2334	3	2.735	0.0038	0.14	1.37	0.062	4.48
2361	2	2.634	0.0205	0.78	1.56	0.143	9.21
2367	3	2.680	0.0082	0.31	2.77	0.090	3.26
2421	4	2.760	0.0052	0.19	1.24	0.072	5.81
2423	5	2.597	0.0160	0.62	4.59	0.127	2.76
2461	2	2.777	0.0007	0.03	0.90	0.027	2.97
2472	5	2.723	0.0166	0.61	2.12	0.129	6.07
2521	3	2.691	0.0236	0.88	1.14	0.154	13.45
2531	6	2.653	0.0385	1.45	3.26	0.196	6.03
2535	11	2.666	0.0137	0.51	3.03	0.117	3.87
2542	3	2.684	0.0298	1.11	1.12	0.173	15.37
2563	6	2.723	0.0110	0.40	1.57	0.105	6.68
2621	4	2.664	0.0232	0.87	1.66	0.152	9.18
2641	3	2.688	0.0110	0.41	0.93	0.105	11.22
2645	7	2.684	0.0388	1.44	1.21	0.197	16.24
2682	3	2.691	0.0276	1.02	1.70	0.166	9.75
ALL	106	2.684	0.0204	0.80	1.963	0.482	24.6

Table 77. Fine Aggregate SSD Bulk Specific Gravity and Absorption.

		Total Variation S_T w/Single-operator Testing Variability					
		SSD G_{mb}			Absorption (%)		
Source #	n	Avg.	St. dv	CV (%)	Avg.	St. dv	CV (%)
2183	2	2.650	0.0078	0.29	1.52	0.30	19.54
2331	3	2.652	0.0090	0.34	1.89	0.01	0.38
2338	2	2.642	0.0000	0.00	1.60	0.02	1.33
2399	2	2.647	0.0049	0.19	2.06	0.11	5.16
2431	4	2.610	0.0395	1.51	1.49	0.42	28.10
2522	6	2.641	0.0046	0.17	1.37	0.07	5.05
2523	3	2.630	0.0075	0.29	1.64	0.08	4.76
2570	15	2.635	0.0193	0.73	1.83	0.24	13.14
2613	2	2.643	0.0021	0.08	1.17	0.04	3.63
2651	2	2.650	0.0163	0.61	1.37	0.13	9.84
2701	3	2.622	0.0283	1.08	2.01	0.45	22.31
2750	5	2.652	0.0298	1.12	1.50	0.42	27.90
ALL	49	2.638	0.0206	0.8	1.65	0.27	16.3

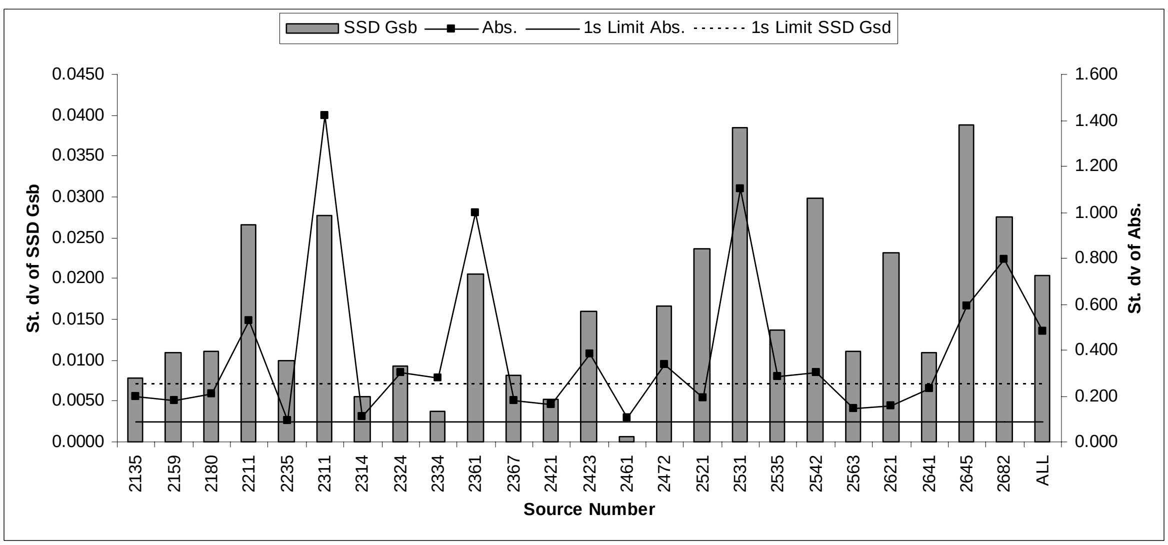


Figure 74. Coarse Aggregate.

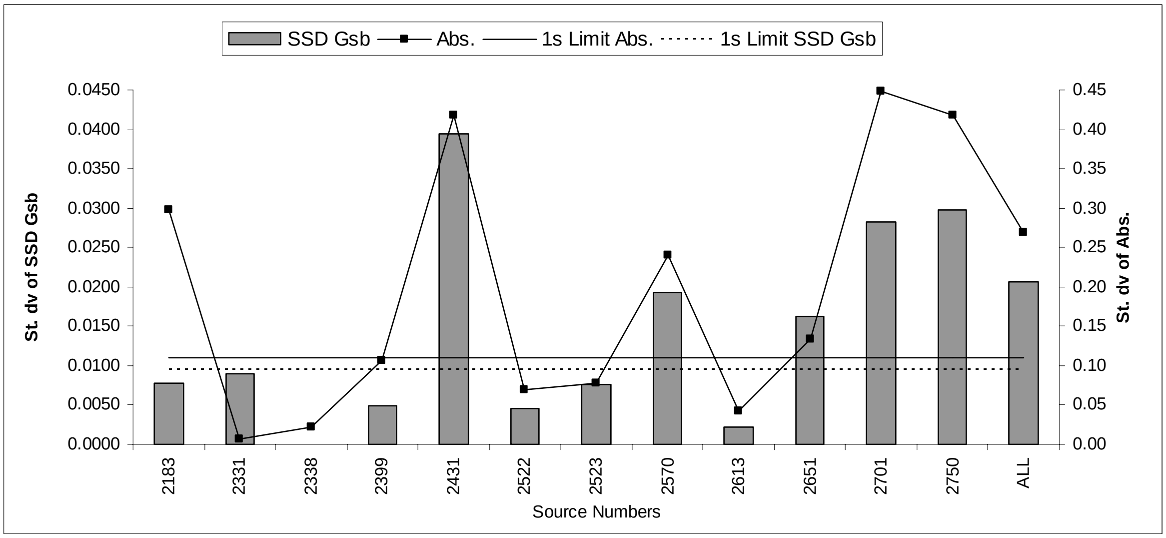


Figure 75. Fine Aggregate.

7.6 Results from Additional Data Analysis

7.6.1 Compressive Strength

The variability from the compressive strength testing was assessed by analyzing the information in data sources VII and VIII. The description of the manner by which the compressive strength results were analyzed is shown in Figure 76, while the results in Table 79 show the single and multi operator variations for data sets VII and VIII. The variation of the data is shown in Figure 77 along with the allowable coefficient of variation (1s) of 2.37%, according to Table 15, for the test. The inherent material, sampling, and testing variability (SS + STE) for the compressive strength data from the superstructure testing (data source VIII) was at or below the allowed (1s) variation of 2.37%. The data that was given in the INDOT SEP was just above the (1s) limit.

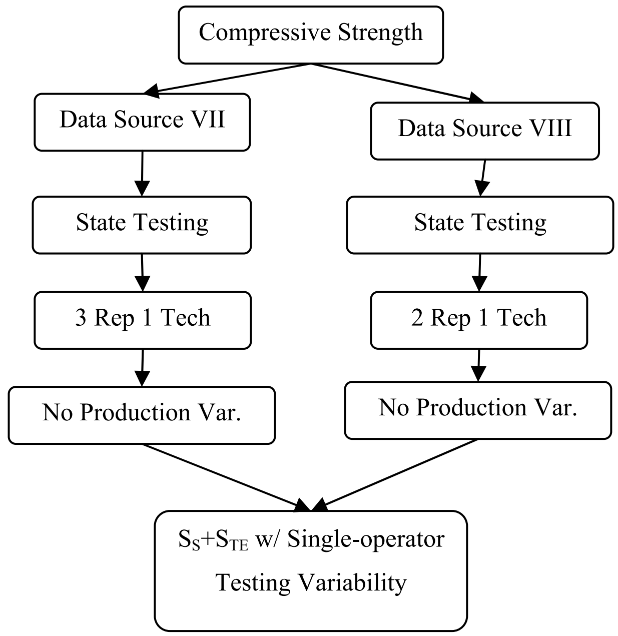


Figure 76. Compressive Strength Data Structure.

Table 78. Compressive Strength, psi.

			Sampling + Testing Variability (S_S + S_{TE}) w/Single-operator Testing Variability		
			State		
Data Source	Project No	n	Avg.	St. Dev	CV%
VII	Sulfur Caps	60	5138	244	3.6
VII	Neoprene Pads	63	5333	181	2.9
VII	ALL	123	5238	214	3.2
VIII	B24458	84	6433	222	2.6
VIII	B25407	135	6237	212	2.4
VIII	B26921	146	6006	181	2.1
VIII	ALL	365	6190	202	2.3

Table 79. Compressive Strength, psi.

Data Source	Project No	n	Total Variation S_T w/Multi-operator Testing Variability, State: Avg.	St. Dev	CV%
VII	Sulfur Caps	60	5138	322	5.9*
VII	Neoprene Pads	63	5333	201	3.8*
VII	ALL	123	5238	267	4.8*
VIII	B24458	84	6749	490	7.3
VIII	B25407	135	6237	692	11.1
VIII	B26921	146	6006	434	7.2
VIII	ALL	365	6263	555	8.5

* Sampling + Testing Variability (S_S + S_{TE}) w/multi-operator Testing Variability

Table 80. Compressive Strength, psi, Variation by Date.

Contract	Date	n	Sampling + Testing Variability (S_S + S_{TE}) w/Single-operator Testing Variability: Avg.	St. Dev	CV%
B24458	9/6/2000	4	6951	41	0.6
	9/29/2000	17	6978	224	3.2
	7/17/2001	5	6904	217	3.1
	8/29/2001	16	6407	247	3.9
B25407	10/22/2002	7	6091	248	4.1
	11/12/2002	7	6011	323	5.4
	12/10/2002	2	5690	32	0.6
	3/22/2003	7	6381	149	2.3
	4/1/2003	11	6806	64	0.9
	7/17/2003	1	6425	389	6.1
	8/5/2003	7	5646	109	1.9
	8/12/2003	7	6111	165	2.7
	8/26/2003	18	6313	261	4.1
B26921	6/22/2004	4	5773	104	1.8
	6/25/2004	3	5890	150	2.6
	6/29/2004	3	6117	116	1.9
	7/8/2004	20	5807	171	2.9
	7/20/2004	2	6353	136	2.1
	7/23/2004	3	5853	35	0.6
	8/10/2004	19	6090	191	3.1
	8/13/2004	8	6325	167	2.6
	8/27/2004	5	5876	49	0.8
	9/3/2004	6	6207	336	5.4

Table 81. Compressive Strength, psi, Total Variation by Date.

			Total Variation S_T w/Multi-operator Testing Variability		
Contract	Date	n	Avg.	St. Dev	CV%
B24458	9/6/2000	8	6951	428	6.2
	9/29/2000	34	6978	425	6.1
	7/17/2001	10	6904	342	5.0
	8/29/2001	32	6407	422	6.6
B25407	10/22/2002	14	6091	385	6.3
	11/12/2002	15	6011	728	12.1
	12/10/2002	4	5690	786	13.8
	3/22/2003	14	6381	906	14.2
	4/1/2003	22	6806	439	6.5
	7/17/2003	2	6425	389	6.1
	8/5/2003	14	5646	441	7.8
	8/12/2003	14	6111	631	10.3
	8/26/2003	36	6313	662	10.5
B26921	6/22/2004	8	5773	229	4.0
	6/25/2004	6	5890	325	5.5
	6/29/2004	6	6117	291	4.8
	7/8/2004	40	5807	463	8.0
	7/20/2004	4	6353	517	8.1
	7/23/2004	6	5853	330	5.6
	8/10/2004	38	6090	462	7.6
	8/13/2004	16	6325	232	3.7
	8/27/2004	10	5876	208	3.5
	9/3/2004	12	6207	407	6.6

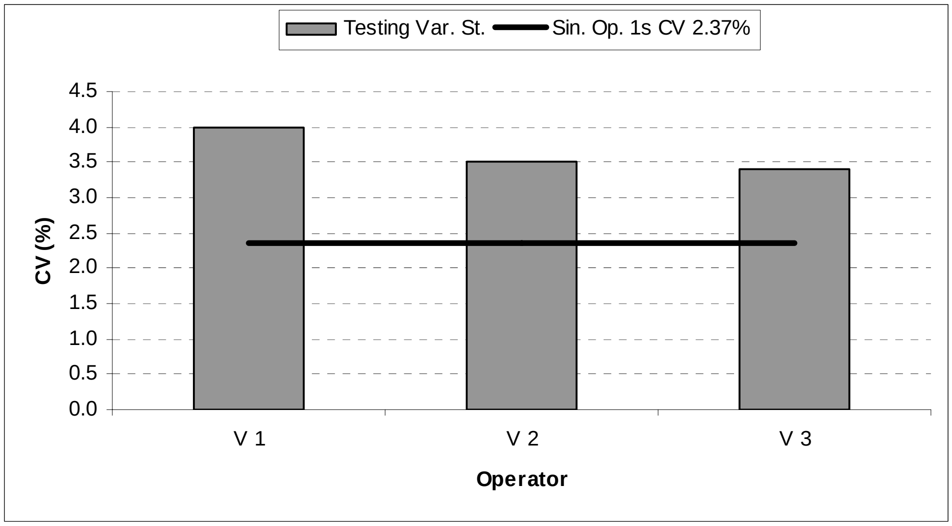


Figure 77. Compressive Strength.

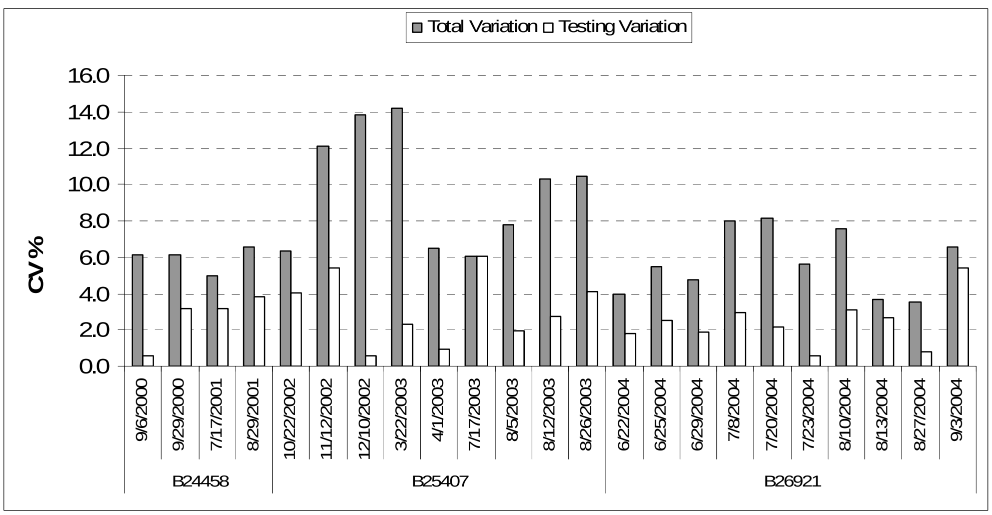


Figure 78. Compressive Strength by Date.

7.6.2 Specific Gravity and Absorption of Aggregates

The variability in the bulk specific gravity and absorption were assessed using data source IX. The description of the manner by which the specific gravity and absorption were analyzed is displayed in Figure 79. The data generated by the INDOT Sample Exchange Program (SEP) was analyzed by comparing all of the replicates for one round of testing.

Through this analysis the inherent material, sampling, and testing variability (SS + STE) was calculated. The data analysis for the job site sampling was conducted using different aggregate sources and comparing the results of one operator within each quarry. The data did not contain replicate test results, therefore testing variability could not be isolated from the total variability (ST). The results of the analysis are displayed in Table 82 through Table 85, while Figure 80 through Figure 85 provide a graphical representation of the variation in comparison to the AASHTO standard, see Table 15. The testing and sampling variation present in the coarse aggregate testing from the INDOT SEP program was at or below the allowable (1s) multi-operator variation. The fine aggregate in the INDOT SEP testing exceeded the allowed variation, indicating that there may be problems with the sampling or testing. The variation from the job site samples is recorded over a large time period and contains additional variability because the replicates were sampled and tested over varying time periods.

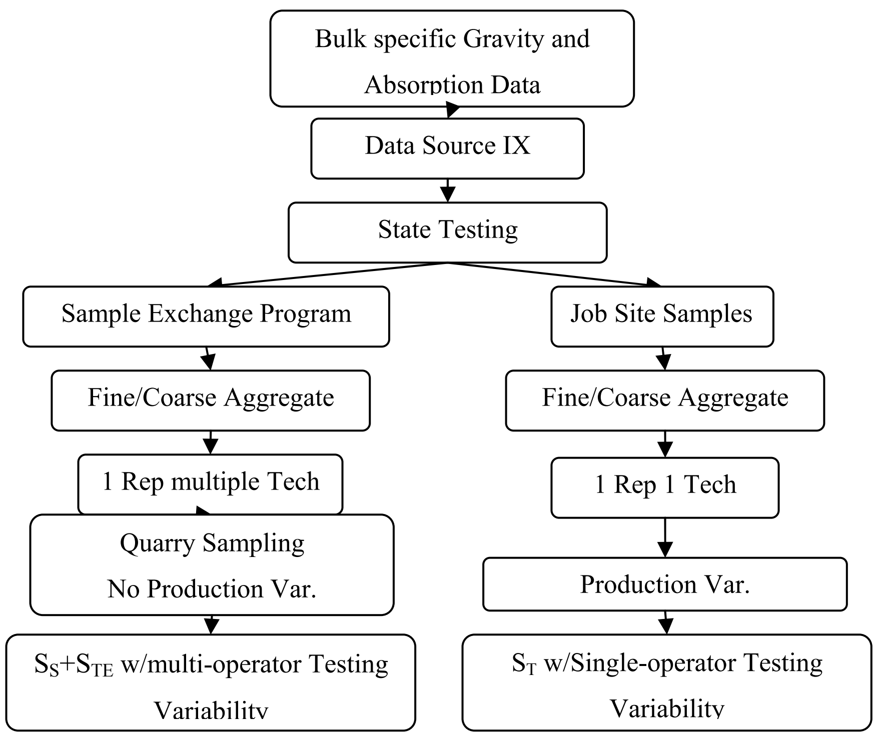


Figure 79. Data Structure of SSD Bulk Specific Gravity and Absorption.

Table 82. Fine Aggregate, SEP Testing.

			Sampling + Testing Variability $S_S + S_{TE}$ w/Multi-operator Testing Variability					
			State					
			Gmb		Gmb (SSD)		Absorption (%)	
Data Source	Data Set	n	Avg.	St. Dev	Avg.	St. Dev	Avg.	St. Dev
IX	SEP #37	16	2.608	0.037	2.645	0.036	1.459	0.258
IX	SEP#38	16	2.553	0.048	2.606	0.046	1.939	0.359
IX	SEP#41	19	2.573	0.044	2.619	0.039	1.780	0.393
IX	SEP#42	19	2.605	0.041	2.642	0.041	1.417	0.218
IX	All	70	2.585	0.043	2.628	0.041	1.644	0.315

Table 83. Coarse Aggregate, SEP Testing.

			Sampling + Testing Variability $S_S + S_{TE}$ w/Multi-operator Testing Variability					
			State					
			Gmb		Gmb (SSD)		Absorption (%)	
Data Source	Data Set	n	Avg.	St. Dev	Avg.	St. Dev	Avg.	St. Dev
IX	SEP#31	10	2.605	0.011	2.645	0.008	1.518	0.153
IX	SEP#32	10	2.612	0.008	2.647	0.006	1.333	0.126
IX	SEP#35	9	2.634	0.022	2.673	0.014	1.499	0.313
IX	SEP#39	23	2.656	0.013	2.691	0.009	1.307	0.165
IX	All	52	2.634	0.014	2.670	0.010	1.386	0.190

Table 84. Fine Aggregate, Job Site Samples.

			Total Variation S_T w/Single-operator Testing Variability					
			Gmb (SSD)			Absorption (%)		
Data Source	Source #	n	Average	Std dev	CV %	Average	Std dev	CV %
IX	2211	3	2.622	0.028	1.08	2.007	0.448	22.31
IX	2314	6	2.641	0.005	0.17	1.365	0.069	5.05
IX	2324	2	2.642	0.000	0.00	1.595	0.021	1.33
IX	2334	2	2.655	0.011	0.40	1.885	0.007	0.38
IX	2421	3	2.646	0.008	0.31	1.513	0.210	13.90
IX	2423	4	2.610	0.039	1.51	1.490	0.419	28.10
IX	2472	3	2.661	0.036	1.36	1.337	0.442	33.04
IX	2521	3	2.630	0.008	0.29	1.640	0.078	4.76
IX	2531	2	2.647	0.005	0.19	2.055	0.106	5.16
IX	2535	10	2.630	0.017	0.64	1.917	0.219	11.42
IX	2563	6	2.646	0.019	0.71	1.715	0.223	13.02
IX	2641	3	2.640	0.020	0.76	1.417	0.131	9.21
IX	2645	2	2.643	0.002	0.08	1.170	0.042	3.63
IX	ALL	49	2.637	0.020	0.62	1.648	0.091	12.36

Table 85. Coarse Aggregate, Job Site Samples.

			Total Variation S_T w/Single-operator Testing Variability					
			Gmb (SSD)			Absorption (%)		
Data Source	Source #	n	Average	Std dev	CV %	Average	Std dev	CV %
IX	2135	6	2.689	0.007	0.27	1.087	0.172	15.84
IX	2159	4	2.676	0.011	0.41	1.375	0.182	13.20
IX	2180	5	2.703	0.011	0.41	0.750	0.207	27.54
IX	2211	8	2.666	0.024	0.88	2.853	0.414	14.52
IX	2232	4	2.686	0.043	1.60	2.995	0.972	32.46
IX	2235	3	2.709	0.010	0.36	2.370	0.095	4.03
IX	2311	3	2.680	0.028	1.03	2.177	1.423	65.38
IX	2314	13	2.652	0.007	0.28	1.458	0.166	11.41
IX	2324	2	2.711	0.002	0.08	1.785	0.460	25.75
IX	2334	3	2.735	0.004	0.14	1.373	0.278	20.24
IX	2335	5	2.697	0.013	0.50	2.010	0.242	12.06
IX	2361	2	2.634	0.021	0.78	1.555	0.997	64.12
IX	2362	5	2.718	0.017	0.63	2.444	0.350	14.34
IX	2367	3	2.680	0.008	0.31	2.773	0.182	6.55
IX	2389	4	2.650	0.022	0.83	4.190	0.447	10.68
IX	2421	4	2.760	0.005	0.19	1.238	0.165	13.32
IX	2423	5	2.597	0.016	0.62	4.594	0.383	8.34
IX	2448	3	2.669	0.066	2.46	2.330	0.233	10.00
IX	2461	3	2.770	0.011	0.41	1.053	0.284	26.99
IX	2472	8	2.726	0.019	0.68	1.929	0.466	24.17
IX	2521	3	2.691	0.024	0.88	1.143	0.189	16.56
IX	2531	8	2.643	0.040	1.52	3.439	1.000	29.07
IX	2535	11	2.666	0.014	0.51	3.025	0.286	9.46
IX	2542	10	2.678	0.016	0.59	1.012	0.227	22.39
IX	2563	6	2.723	0.011	0.40	1.572	0.142	9.05
IX	2621	8	2.682	0.026	0.96	1.431	0.284	19.83
IX	2641	3	2.688	0.011	0.41	0.933	0.234	25.02
IX	2645	13	2.672	0.033	1.23	1.215	0.491	40.42
IX	2682	3	2.679	0.017	0.62	1.147	0.471	41.04
IX	ALL	158	2.682	0.022	0.71	1.975	0.453	20.69

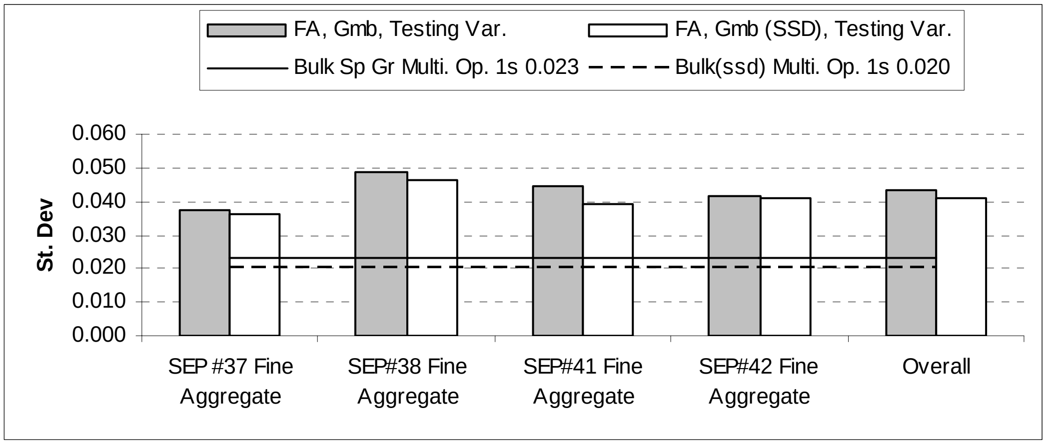


Figure 80. Fine Aggregate SEP G_{mb}, G_{mb} (SSD).

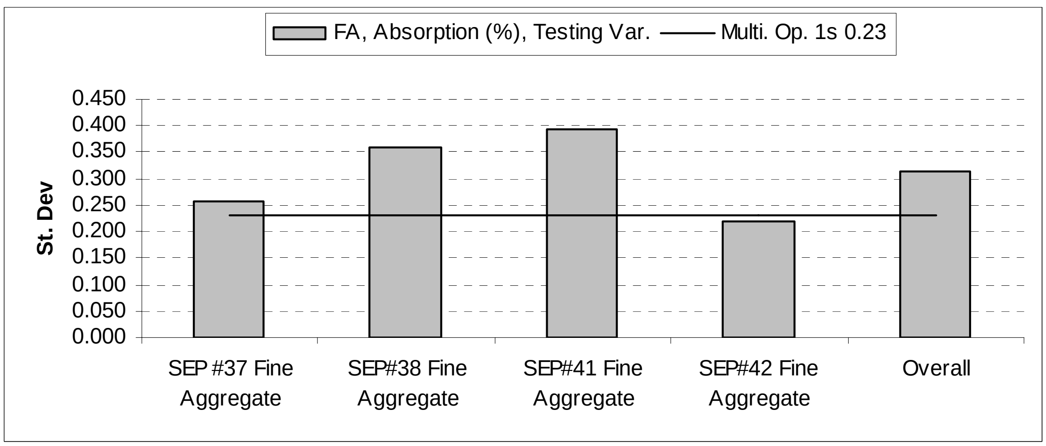


Figure 81. Fine Aggregate SEP Absorption.

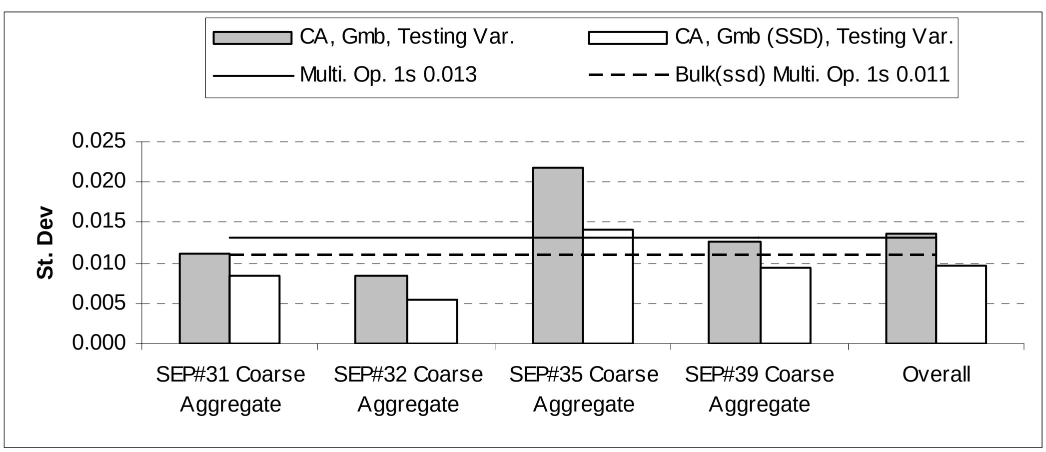


Figure 82. Coarse Aggregate SEP G_{mb}, G_{mb} (SSD).

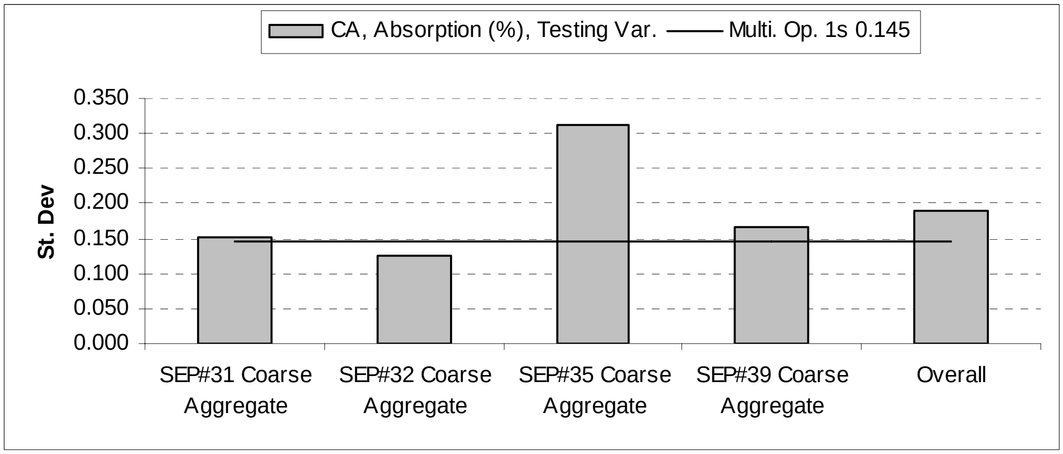


Figure 83. Coarse Aggregate SEP Absorption.

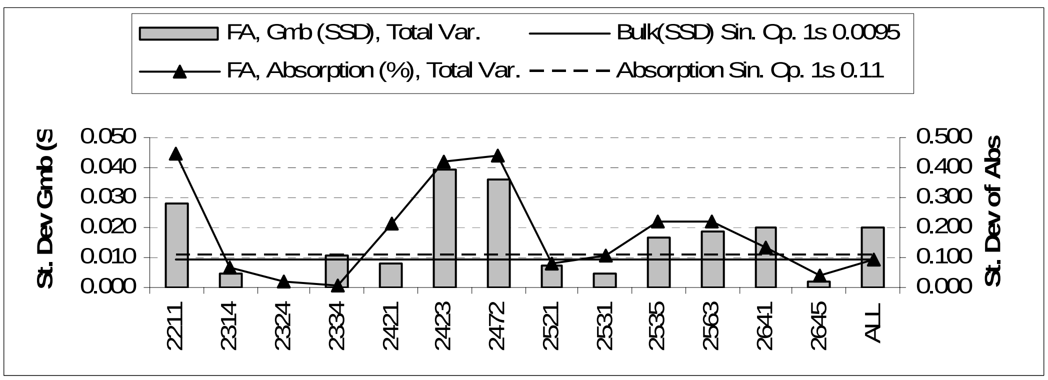


Figure 84. Fine Aggregate Job Site Samples G_{mb} (SSD) and Absorption.

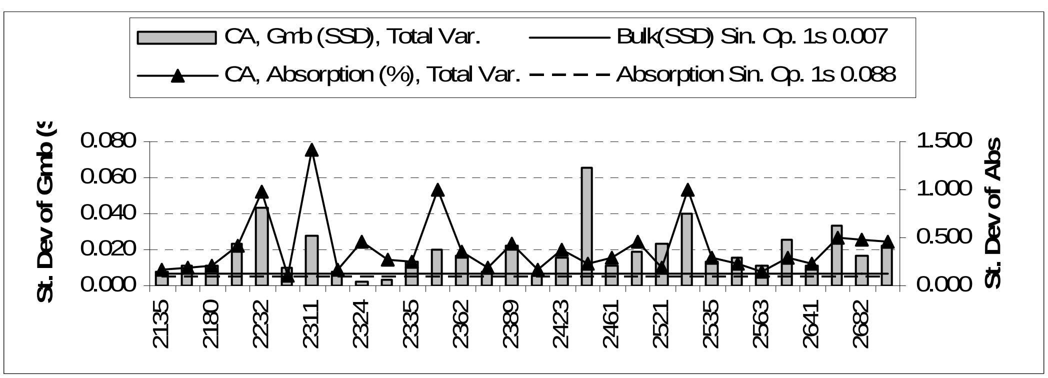


Figure 85. Coarse Aggregate Job Site Samples G_{mb} (SSD) and Absorption.

7.6.3 Pavement Thickness

The pavement thickness was calculated using data source X. The data analysis procedure that was used for pavement thickness is shown in Figure 86 while Table 86 and Table 87 show the calculated total and testing variability from the laboratory testing. The total and testing variability in the measured pavement thickness was low; however there is currently no information on the inherent material, sampling, and testing variability or standard to provide a comparison for the standard deviation.

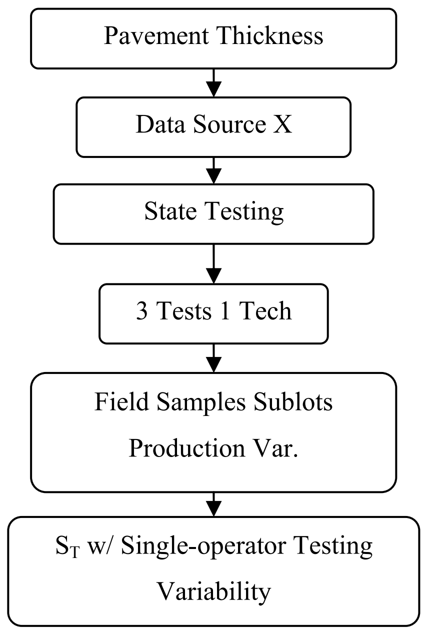


Figure 86. Pavement Thickness Data Structure.

Table 86. Multi-Operator Total Variability.

Data Source	Sample	n	Average	St. Dv	CV (%)
X	38088	6	10.48	0.041	0.39
X	38089	6	14.42	0.041	0.28
X	All	12	12.45	0.041	0.33

Table 87. Single Operator Variability.

Data Source	Sample	n	Average	St. Dv	CV (%)
X	38088	6	10.48	0.041	0.28
X	38089	6	14.42	0.041	0.20
X	All	12	12.45	0.041	0.24

7.6.4 Plastic Air Content

The plastic air content was also computed with superstructure data from data source VIII. A description of the manner by which the plastic air content results were obtained is shown in Figure 87. It can be seen that the data source can provide information on production variability. Results from the analysis show the total measured variability in Table 88 and 86. Figure 88 shows the variation by contract and test date.

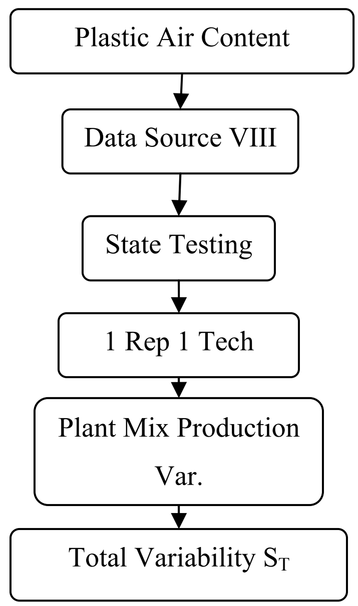


Figure 87. Plastic Air Content Data Flow Chart.

Table 88. Plastic Air Content, % (Total Variability).

Data Source	Contract	n	Avg.	Std. Dev	COV
VIII	B24458	42	6.5	0.498	6.83
VIII	B25407	68	7.1	1.396	16.64
VIII	B26921	73	6.6	0.786	10.50
VIII	ALL	183	6.8	1.012	11.93

Table 89. Plastic Air Content, % by Date (Total Variability)

Contract	Date	n	Avg.	Std. Dev	COV
B24458	9/6/2000	4	6.1	0.785	12.980
	9/29/2000	17	6.5	0.663	10.149
	7/17/2001	5	6.0	0.466	7.738
	8/29/2001	16	6.7	0.478	7.111
B25407	10/22/2002	7	7.1	0.977	13.735
	11/12/2002	8	8.2	1.568	19.066
	12/10/2002	2	5.6	1.838	32.830
	3/22/2003	7	7.6	2.224	29.265
	4/1/2003	11	7.1	1.071	15.180
	8/5/2003	7	6.4	1.290	20.285
	8/12/2003	7	7.0	1.336	19.210
	8/26/2003	18	7.1	1.130	15.981
B26921	6/22/2004	4	6.5	0.566	8.703
	6/25/2004	3	6.7	0.500	7.463
	6/29/2004	3	6.0	0.520	8.660
	7/8/2004	20	6.8	1.217	17.853
	7/20/2004	2	5.8	1.838	31.698
	7/23/2004	3	6.0	0.611	10.240
	8/10/2004	19	6.7	0.643	9.594
	8/13/2004	8	6.8	0.506	7.448
	8/27/2004	5	7.0	0.593	8.452
	9/3/2004	6	6.3	1.003	15.876

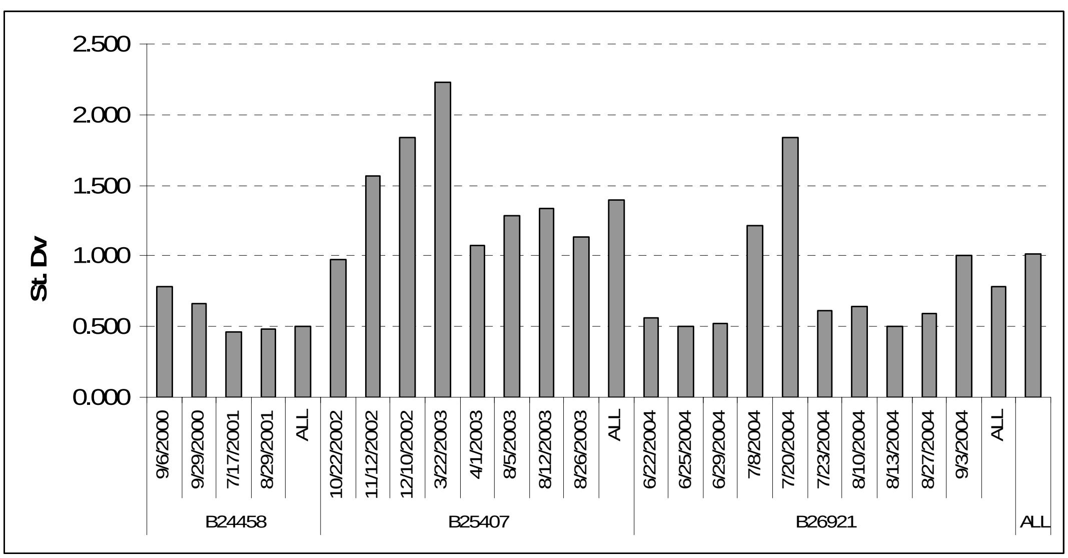


Figure 88. Plastic Air Content Contract Variation by Date.

8 SUMMARY OF FINDINGS AND RECOMMENDATIONS

8.1 Summary of Findings

The objective of the study was to assess the variability that is associated with INDOT QC/QA testing procedures and their interpretation. Variability can be attributed to the "testing variability" that includes inherent material, sampling, and testing variability, and "production variability" includes the variability associated with production. All of these combined are responsible for producing the total variation, which is measured by various testing protocols. Due to brevity, the combined inherent material, sampling, and testing variation will be referred to as testing variation in the following text.

This study was performed by analyzing the existing test data that had been collected by INDOT and INDOT contractors, on paving and superstructure contracts in Indiana, as well as conducting a laboratory study that was performed at Purdue University. The objective of the laboratory study was to assess the test methods that turned out to be problematic based on the findings from the analysis of existing data, or study test methods for which previous test data was not available. A summary of the key findings are listed below.

<u>Results for HMA:</u>

Overall it can be concluded that the hypothesis of increased testing variation associated with the calculated quantities, presented in the problem statement, turned out to be false. As discussed in Chapter 1 research has indicated (Hand and Epps, 2000) that the allowed variability in the materials testing can lead to unacceptable variation of the calculated quantities computed from the acceptable test results. Based on Monte Carlo simulation, the allowed variation in the tested bulk and theoretical maximum specific gravity values for asphalt concrete mixtures could produce unacceptable air void content variation. The simulation runs used ASTM precision statements.

There are two reasons why this hypothesis turned out to be false. Firstly, an important change during the course of this research has taken place, namely, a change in the ASTM precision statements. A new 2004 version of the ASTM D2726 method which measures the bulk specific gravity of compacted mixture has a considerably tighter precision statement compared to the older version of the method. The new ASTM precision statement is now in agreement with the AASHTO precision statement.

The second reason that this hypothesis is false is that the actual measured testing variation is smaller than was estimated based on the Monte Carlo simulation using the "old" ASTM precision statements. Research showed that the measured and theoretical or allowed AASHTO (1s) limits agreed very well.

An important part of the study was to assess the precision statements for the calculated volumetric quantities, SGC pill air voids content, in-place density and pill VMA. The ASTM D4460 standard: "*Calculating Precision Limits Where Values are calculated from Other Test Methods*" gives equations to obtain the precision limit for the air voids content, but (1s) limit for the VMA has not existed. Based on the ASTM D4460 two equations, Equation (21) and (22) given below, were developed for obtaining the (1s) limit for the VMA. $\sigma_{x/y}$ is the (1s) limit for VMA while G_{mb} is the mix bulk specific gravity, P_b is the binder content, and G_{sb} is the aggregate bulk specific gravity. σ_{Gmb}, σ_{Pb}, and σ_{Gsb} are the (1s) limits for the mix bulk specific gravity, binder content, and aggregate specific gravity, respectively. Binder content and precision must be given in decimal form.

$$\sigma_{xy} = \sqrt{(1-P_b)^2(\sigma_{Gmb})^2 + (G_{mb})^2(\sigma_{Pb})^2} \qquad (21)$$

$$\sigma_{x/y} = \sqrt{\frac{(G_{sb})^2(\sigma_{xy})^2 + [(1-P_b)*G_{sb}]^2(\sigma_{Gsb})^2}{(G_{sb})^2}} \qquad (22)$$

The following observations of the testing variation associated with the INDOT QC/QA testing is based on the AASHTO (1s) limits of 0.32 for the air voids content/density and 0.25 for the pill VMA in addition to the (1s) limits given for each test method by AASHTO. The AASHTO T275 (1s) limit of 0.007 was used for all mixture bulk specific gravity evaluation.

From the analysis of the INDOT volumetric acceptance and quality control data measured by INDOT and contractors between 2001 and 2002 the following observations were made:

- The testing variation for the gyratory pill and core bulk specific gravity G_{mb} tests was within (0.0022 to 0.0066) of the allowable AASHTO T275 (1s) limit (0.007).
- The testing variation for the maximum theoretical specific gravity G_{mm} tests was above (0.0079) the allowable AASHTO T209 (1s) limit (0.004). This was further investigated in laboratory study conducted by Purdue.
- Testing variation was not increased by increase in the aggregate nominal size.
- The estimated testing variation for the gyratory pill air voids content (0.27 -0.31) was within the AASHTO (1s) limit (0.32). The total variation ranged from 0.73 to 0.93 suggesting that 60% of the total variation was associated with the production variation.
- The estimated testing variation for the gyratory pill VMA was slightly above (0.24-0.31) the AASHTO (1s) limit (0.25). The total variation ranged from 0.56 to 0.62 suggesting that up to 50% of the total variation was associated with production variation.
- The estimated testing variation for the core air voids content and density was within or slightly above 0.35 to 0.42 the AASHTO (1s) limit (0.32). The total variation ranged from 1.41 to 1.52 suggesting that 80% of the total variation was associated with the production variation.
- Testing variation could not be assessed for binder content because lack of replicate tests. The total variation ranged from 0.23 to 0.26. If AASHTO (1s) limit (0.004) is used for testing variation then approximately 85% of the total variation was associated with the production variation.

Based on the information presented above, the total variation in terms of statistical probability of test data being outside the tolerance limits (being in penalty range) were estimated to be as follows:

- The overall mean for SGC pill air voids content was 3.6% while the target is 4%. With one-sigma total variation of (0.93) there is 95% probability that 33% of the test data is outside the air voids content tolerance limits of 4 ±1%.

- The overall mean for SGC pill VMA was 14.06% while the average target from each JMF was 14.48%. With one-sigma total variation of (0.62) there is 95% probability that 17% of the test data is outside the VMA tolerance limits of 14.48 ±1%.
- The overall mean for binder content was 5.31% while target was not specified in the database. With one-sigma total variation of (0.26) there is 95% probability that 5% of the test data is outside the binder content tolerance limits of ±0.5% if the measured P_b is exactly the target P_b.
- The overall mean for core density (T166) was 92.4% while the full pay target is 92.5%. With one-sigma total variation of (0.35) there is 95% probability that 39% of the test data is in the penalty range having less than 92% density.
- The overall mean for core density (T275) was 90.9% while the full pay target is 92.5%. With one-sigma total variation of (0.42) there is 95% probability that 73% of the test data is in the penalty range having less than 92% density.

From the analysis of the INDOT Exchange Data the following observations were made:

- The testing variation for the maximum theoretical specific gravity G_{mm} tests was way above (0.0172) the allowable AASHTO T209 testing variation limit (0.004). This was further investigated in laboratory study conducted by Purdue.
- The testing variation for fine aggregate apparent, bulk and SSD bulk specific gravity (0.0264, 0.038, 0.0299), and water absorption (0.41) tests exceed the allowed AASHTO T84 limits (0.0095, 0.011, 0.0095, 0.11). This was further investigated in laboratory study conducted by Purdue.
- The testing variation for coarse aggregate apparent, bulk and SSD bulk specific gravity (0.013, 0.009, 0.010), and water absorption (0.046) tests partially exceed allowed AASHTO T85 limits (0.007, 0.009, 0.007, 0.088). This was further investigated in laboratory study conducted by Purdue.

From the analysis of the INDOT Ignitions Study the following observations were made:

- The testing variation for the binder content P_b was outside (0.006) the AASHTO T308 (ITM 586) single-operator limit (0.004) but within a multi-laboratory limit (0.006).

From Purdue laboratory study the following observations were made:

- The fine and coarser aggregate testing variation for AASHTO T84 and T85 were within or slightly above the AASHTO limits for stone aggregates and aggregates with low water absorption (<2%).
- The fine and coarser aggregate testing variation for AASHTO T84 and T85 were above the AASHTO limits for slag and stone aggregates with high water absorption (>4%).
- The G_{mm} testing variation was within the AASHTO T209 limit for the G_{mm} and supplemental procedure.

The Purdue laboratory study also investigated Instroteck Corelok method and the following observations were made:

- The fine and coarser aggregate testing variations measured by the Corelok method were considerably above the AASHTO T84 and T85 (1s) limits.
- The bias in the fine aggregate testing was within the multi-laboratory AASHTO difference two-sigma (d2s) limit while the bias in the coarse aggregate testing was considerably above the (d2s) limits.
- Manufactured sand gave more variable test results compared to natural sand.
- The G_{mm} testing variation measured by Corelok method was above the AASHTO (1s) limit for standard T209 test but the bias between T209 and Corelok test results was within or slightly above the allowed difference for multi-laboratory (d2s) limit.

<u>Results for PCC:</u>

From the analysis of the PCC data collected and measured by INDOT and INDOT contractors the following observations were made:

- The testing variability for the plastic air content test was within the allowable limits (0.28%) with values that ranged from 0.12% to 0.21%. The total variability in concrete pavements ranged from 0.37% to 1.29% thereby suggesting that the majority of the variability was associated with production.
- The testing variability for the plastic unit weight was within the allowable limits (0.82 lb/ft^3) with values that ranged from 0.35 lb/ft^3 to 0.52 lb/ft^3. The total variability ranged from 0.86 lb/ft^3 to 2.20 lb/ft^3 thereby suggesting that the majority of the variability was associated with production.
- The testing variability for the flexural strength were generally within the allowable coefficient of variation limits (5.7% and 7.0%) with values that ranged from 2.4 to 6.5%. The total variability included variation of up to 13.3%.
- The compressive strength data from data sources VII and VIII indicated a variability that was at the AASHTO (1s) limit. Data from both a laboratory study and production samples exhibited about the same testing variability that was at the AASHTO (1s) limit (COV of 2.37%). The compressive strength data from data source V had a COV of 3.7% and was higher than the AASHTO allowable limits. This analysis however was performed using a relatively limited series of data that are based on a single laboratory study.
- The variability of the splitting tensile strength test was below the AASHTO (1s) limit of COV 5.0%.
- INDOT thickness testing in data source X yielded the testing variability limit 0.047 for single operator variation. The total variability of thickness testing for one paving project in data source IV was also observed to be relatively low.
- The study on the variability of the specific gravity of aggregates was conducted to assess variation in aggregate properties from aggregates from the same source over time. The results of this analysis yielded the expected variability of those tests over time and their variability dependent on the source. This may be expected based on variations in mining operations.

8.2 Recommendations for HMA

Based on the study findings, it is recommended that INDOT uses (1s) of 0.32 for the SGC pill air voids content and in-place density precision, and (1s) of 0.25 for the pill VMA precision. The recommended VMA limit of 0.25 is quite tight; however, a tight limit can be justified due to the fact that the variation in the VMA values is highly detrimental for the in service pavement performance.

It is also recommended that INDOT establishes a quality control procedure to verify the correctness of the maximum specific gravity G_{mm} testing during production. This can be accomplished by randomly running replicate tests. Also periodical testing of aggregate bulk specific gravity G_{sb} during mix production may help reduce the observed bias between mix design and field VMA values.

Based on limited laboratory testing it is recommended that Corelok method is not used to replace the AASHTO T85 testing for the coarse aggregate specific gravity testing without further study of test method deviations. However, the bias observed between the AASHTO T84 and AASHTO T209 is within or slightly above the multi-laboratory (d2s) limit which suggest that Corelok testing could be used instead of the traditional testing. However, it is recommended that these test methods are not used interchangeably within a project.

The current pavement target in-place density of 92% of MSG for the full pay allows over 39% of the asphalt pavements produced in Indiana to have more than 8% air voids content and thus being water permeable. To reduce the high air void content and assure impermeable pavement it is recommended that a lower in-place target density for the full pay range is established.

Based on the overall variation of 0.93% the SGC pill air voids content values ranged from 0 to 7%. Then, statistically about 26% of the compacted pills had lower than 3% air voids content, and about 7% of the pills had higher than 5% air voids content. It is very unlikely that the production variation including raw material variation can explain such a large variation of the compacted mixture properties. Therefore, it is possible that there are other factors, which are contributing to the variation, such as moisture in the mix, variation in gyratory compaction temperature, poorly calibrated gyratory, reheating of the mixture, etc. Therefore it is recommended that before applying any changes to the current specification limits a more thorough investigation of the causes of air voids variation is conducted.

8.3 Recommendations for PCC

Based on the study findings, it was observed that both the INDOT and contractor testing protocols had variation that was essentially equal to or lower than those identified in the corresponding ASTM and AASHTO standards. This demonstrates that high quality testing is commonly performed in the state of Indiana and illustrates clear benefits of the technician certification programs and INDOT educational and training procedures.

The data indicates that while INDOT and the contractors had a low testing variation the total variation could vary significantly from project to project. This implies that different contractors implement and utilize different quality control practices. It is recommended that INDOT work with contractors to develop an incentive plan that encourages contractors to have improved consistency. Life-cycle simulations can be used to demonstrate that improved consistency results in improved long-term performance of concrete pavements (PAVESPEC 2002). As such the INDOT is encouraged to reevaluate their pay factors for strength, air and thickness to offer incentives for contractors with reduced production variation. Further, INDOT is encouraged to consider additional non-destructive testing procedures that can be used to enable production variation to be measured more frequently on paving and superstructure projects.

Discussions with INDOT personnel performing the thickness test indicated potential difficulties, especially in thick pavements, if the core is not taken directly perpendicular to the pavement surface. INDOT should consider the development of procedures to account for this difficulty considering possible modifications to the current testing procedures.

Based on the variation in aggregate properties over time it is recommended that INDOT consider procedures to encourage producers to use more frequent testing to determine accurate aggregate specific gravity and absorption parameters for performing mixture designs and quality control procedures.

9 IMPLEMENTATION PLAN

Implementation of the research includes assessing the current pay factor limits and their correctness against the obtained testing and production variation. This can be done by comparing production variation and total variation to the acceptable testing variation limits.

Generally, the AASHTO/ASTM test method precision statements provide information about the minimum variability that INDOT should specify. Figure 89 illustrates how this information can be used in establishing target, incentive, and disincentive variability ranges. It can be argued that the total variation (σ_{Total}) that would be measured in samples taken during the construction of a project can be determined from Equation (23):

$$\sigma_{Total} = \sqrt{\sigma_{Te}^2 + \sigma_P^2} \tag{23}$$

where the testing variation is denoted as σ_{Te} and the production variation is denoted as σ_P. The testing variation can be plotted as a function of production variation. As expected, the testing variation is constant irrespective of the production variation that may be experienced. The total overall variation is similar to the testing variation at low production levels; however, when high production variation is experienced the total variation becomes very similar to the production variation. Between low and high production variation the total variation is higher than both the testing and production variation.

It would be logical for INDOT to expect the contractor to have some production variation; therefore a target range of variation could be considered that would include some production variation and testing variation. It should be noted however that INDOT would want to discourage contractors from having high production variation. To encourage contractors to improve their process control INDOT could institute a penalty range for high levels of production and total variation. If INDOT chooses to reward the contractor for a high level of production control an incentive range could be imagined for production ranges below the target range. It should however be noted that minimizing the total variation should be rewarded only to a certain level after which time any variation that is measured is likely attributed nearly completely to testing variation.

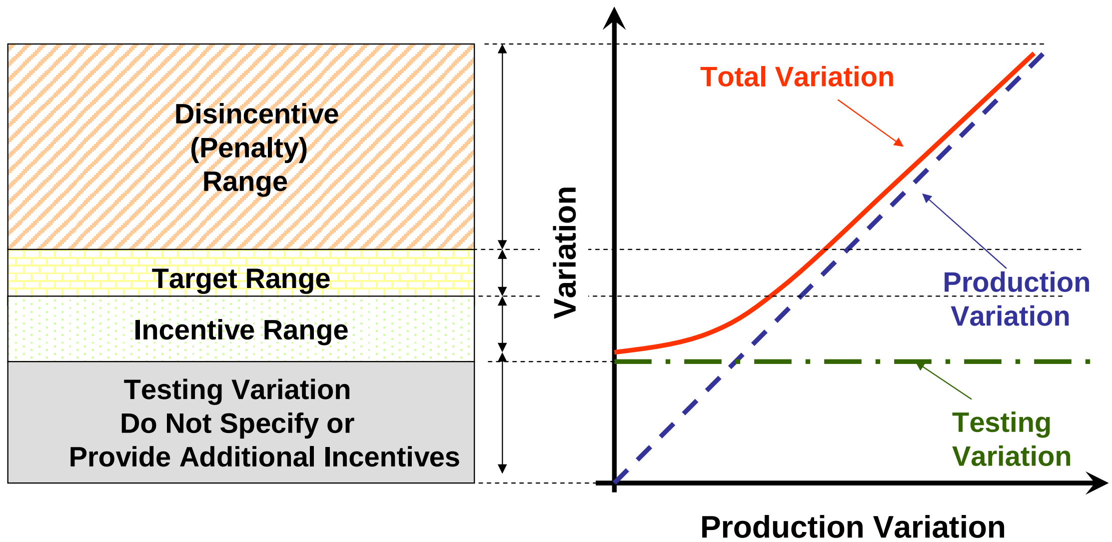


Figure 89. A conceptual illustration of incentive, target, and disincentive variation ranges as a function of testing variation and production variation.

Implementation Examples for HMA:

INDOT's pay factor limits for HMA can be assessed using the analysis results summarized in Table 90. The table lists the actual statistically estimated testing variation and variation that can be specified for each test method based on the AASHTO (1s) specification limits. The table shows a summary of the ranges for typical values measured from INDOT paving projects constructed by various contractors. This information provides guidance to INDOT as to what variations may be anticipated using typical contractor practices in Indiana. Table 90 also shows the "average" variation that was obtained from the INDOT road plate samples tested by contractor or by the state. A more comprehensive summary of testing variation including contractor truck sample testing is presented in Appendix G.

Table 90. HMA Variability Table.

Parameter	Test Method	State or Contactor Road Plate Samples			
		Measured Testing Variation	Testing Variation AASHTO (1s)	Range of Total Variation	Average Total Variation
Pb (%)	ITM 586	0.062[a]	0.04	0.13-0.28	0.26
Pill Va (%)	AASHTO PP28	0.31	0.32	0.070-1.20	0.93
Pill VMA (%)	AASHTO PP28	0.31	0.25[b]	0.48-1.18	0.62
Core Density (%)	AASHTO T166	0.35	0.32	0.90-1.99	1.52
Core Density (%)	AASHTO T275	0.42	0.32		1.41

a) From Ignition Data Analysis, b) Adjusted (1s) for constant G_{sb}

While Figure 89 conceptually illustrates the idea of assessing testing variation, the values from Table 90 were used to construct these diagrams for SGC pill air voids content and VMA, binder content, and in-place density.

Figure 90 shows plots of calculated testing, production and total variation for each pay factor item retrieved from the INDOT's volumetric acceptance database collected between 2001 and 2002. Also, the AASHTO (1s) limits for acceptable testing variation are shown for comparison. The figure shows that depending on the pay item, the testing variation measures differently compared to the total variation. In addition, for some pay factor items such as VMA and binder content the calculated testing variation was larger than the allowed testing variation. The magnitude of testing variation affects to the incentive range because there is no point to give incentive if the testing variation cannot be separated from the improvement in production.

Typically, it is understood in the statistical quality assurance protocols that about 5% of the production can lay outside the tolerance limits and production is still considered to be in control. Then, the target range of production in relation of the total production variation expected in each pay factor item must be specified. This then relates to the physical specifics of a production control to guarantee that a poor production control can be distinguished from a typical good production control.

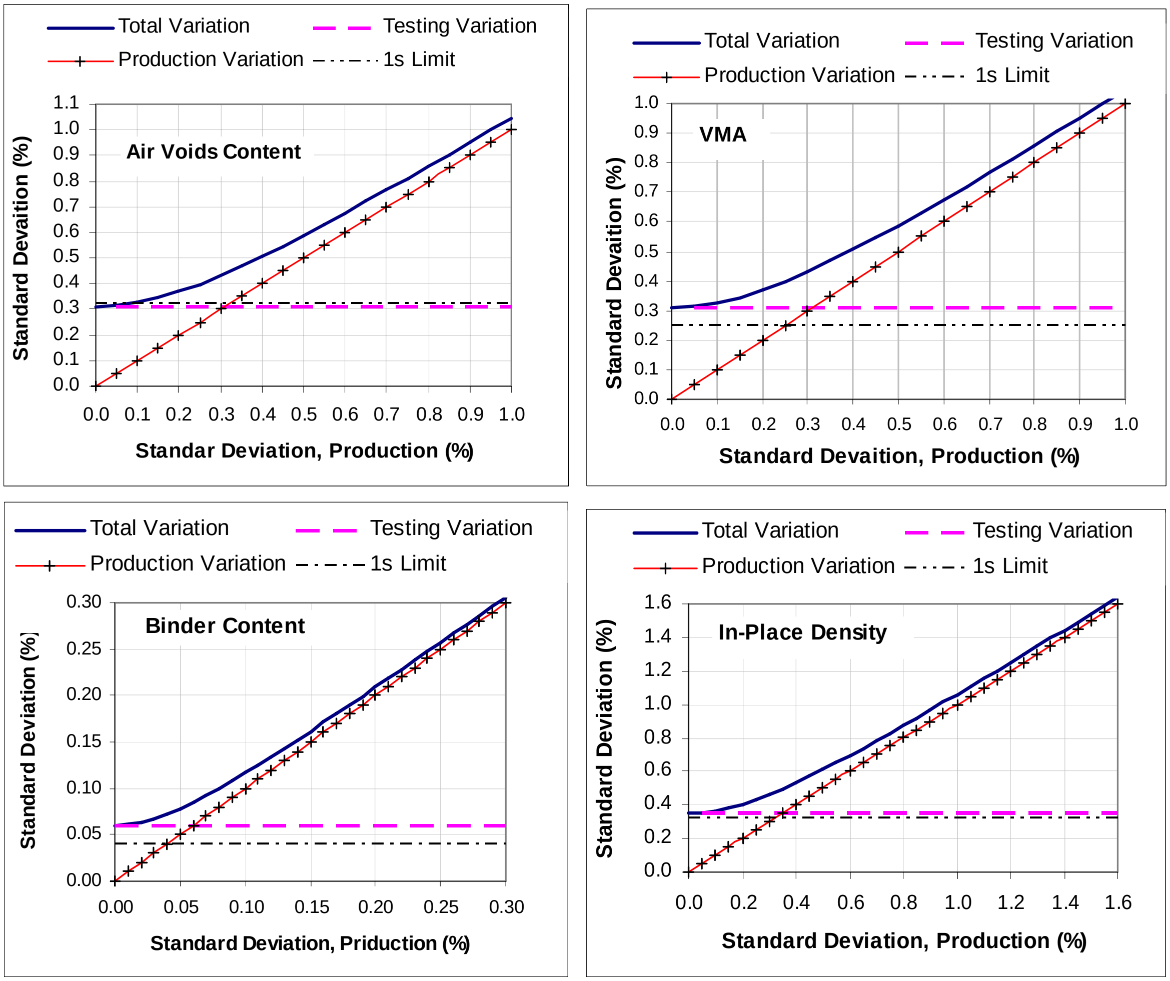


Figure 90. Contribution of Testing and Production Variations to the measured Overall Total Standard Deviation.

Figure 91 shows a probability distribution function (pdf) for a pay item in this case for the pill air voids content, which shows a two sided confidence limit of the mean of 4% air voids content. The 95% confidence limit refers to the ± two sigma limit which states that at 95% probability the production lies between 3% and 5% air voids content. The total variation σ associated to this confidence limit can be calculated using Equations (21) and (22) given in Chapter 5.

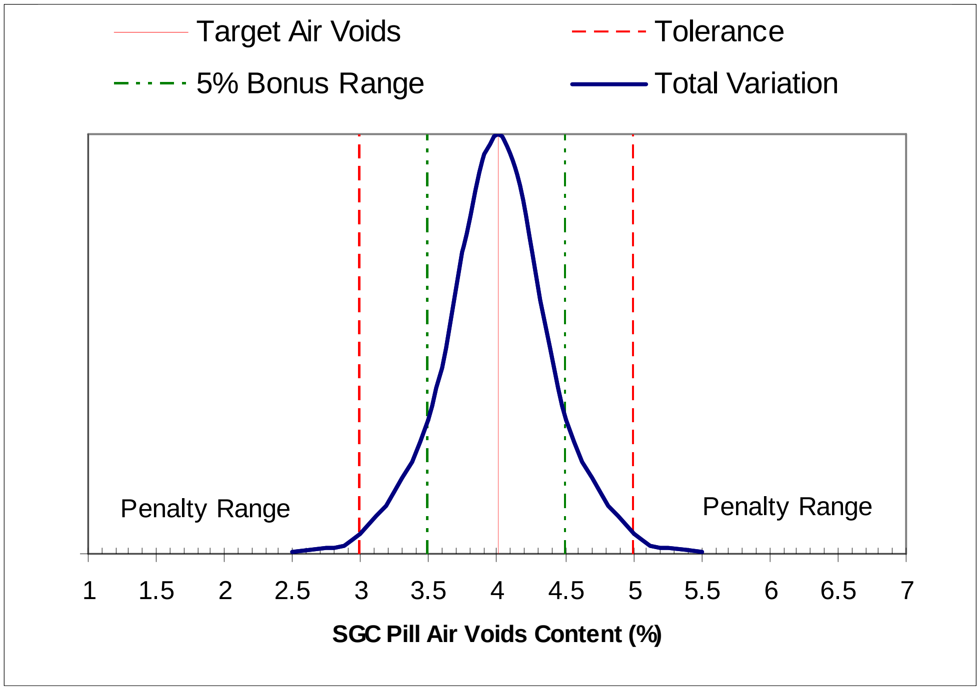


Figure 91. 95% Confidence Limit for Production being Within Tolerance Limits.

Figure 92 shows the total sigma variation which is associated to the tolerance limits in order to have production in the full pay/bonus range. For the SGC pill air voids content, the total variation σ has to be less than 0.50 to have 95% of the production with the tolerances of 4±1% air voids content. The same limit applies to the SGC pill VMA because the acceptance tolerance is the same ±1%. Then, the required total variation for production to be within JMF±1% is also 0.50. The estimated total variation for the VMA was 0.62 while the pill air voids variation was 0.93. Therefore, it is easier to reduce the air voids content variation than to reduce variation of VMA.

The acceptance tolerance for the binder content is JMF ±0.5%. This allows the total variation to be approximately 0.25 in order to have 95% of the production in the full pay range. The estimated total variation was 0.26 which produced about 3% of samples outside the tolerance limits of ±0.5%.

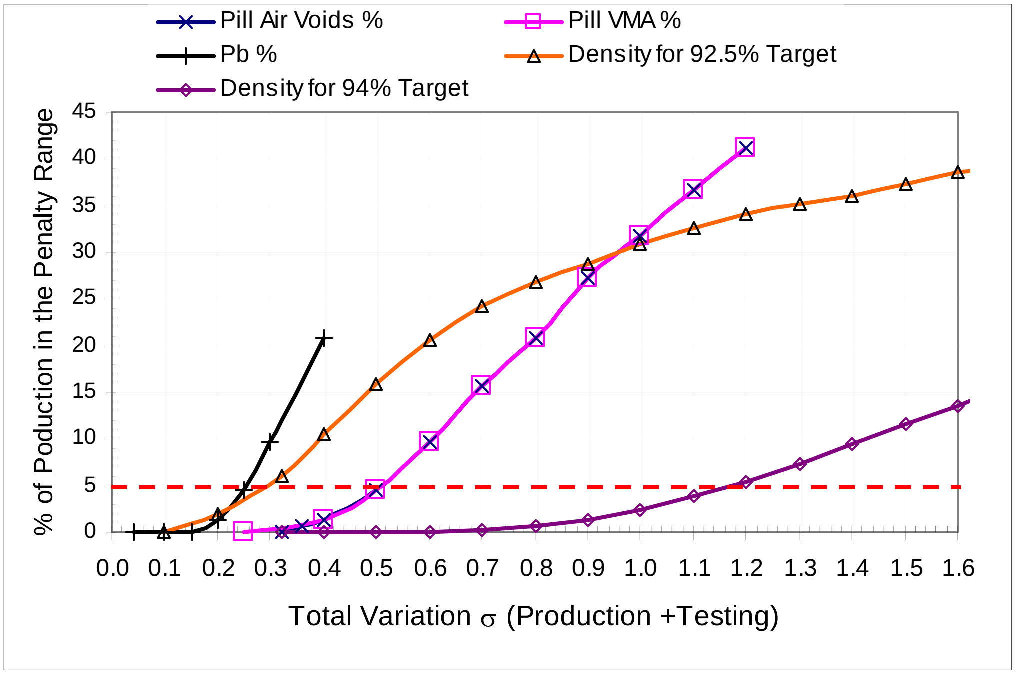


Figure 92. Percent of Production in the Penalty Range.

INDOT's current HMA specification has two targets for the in-place core density; a target for the full pay range (92.5% of MSG) and another target for the 5% bonus range (94% of MSG). If the target pavement density is 94% and tolerance is -2% and +3% of 94%, then the total variation σ can be up to 1.2 to have 95% of the production to be within the full pay range. If the target density is 92.5% and tolerance is -0.5% and + 4.5%, then with the same total production variation σ = 1.2 approximately 34% of the production is in the penalty range, as Figure 92 shows. Furthermore, with the 92.5% target density the required total variation to have less than 5% of the production in the penalty range is less than testing variation of 0.32. Therefore, it is physically impossible to be within the acceptable air voids range if the target for the in-place density is set to 92.5%. Thus, it is recommended that the target for the in-pace density be set closer or at 94% of MSG.

If the targets for density are kept as they currently are, it means that more than 39% of the asphalt pavements produced in Indiana will have air voids content greater than 8%. The 39% refers to the fact that the estimated average (mean) air void content was lower than the target of 92.5% for which the 34% in the Figure 92 refers. When asphalt pavement has air voids content higher than 8% it is water permeable. This makes pavement vulnerable for moisture related damages such as stripping, raveling, pot hole formation, and eventually cracking due to fatigue.

Implementation Examples for PCC:

INDOT's pay factor limits for PCC can be assessed using the results summarized in Table 91. The table indicates the minimum variation that should be specified for each test method used for determining INDOT's acceptance criteria or incentive pay factors. In addition, Table 91 includes a summary of the ranges for typical values measured on selected INDOT projects. This information provides guidance to INDOT as to what variations may be anticipated using typical contractor practices in Indiana. A more comprehensive summary of test data is presented in Appendix H.

Table 91. PCC Variability Table.

Test Method	Parameter	Number of Tests in a Sample	Testing Variation (Minimum to Specify)	Total Variation Range
ITM 404	Pavement Thickness	2	0.051 in	0.31 in
ASTM C39	Compressive Strength	2	4.8%[a]	8.5%[a]
AASHTO T97	Flexural Strength	2	5.7%[a,b]	6.2-13.3%[a,b]
AASHTO T152	Plastic Air Content	1	0.28% by volume	0.41-1.01% by volume
AASHTO T121	Plastic Unit Weight	1	0.65 lb/ft^{3b}	1.22 lb/ft^{3b}

a) Coefficient of Variation, b) Single Operator Variation

While Figure 89 illustrates these ideas conceptually, the values from Table 91 were used to construct these diagrams for flexural strength, compressive strength, air content, and pavement thickness. In addition to using Figure 89, a second figure is used to relate the total variation with the confidence level (confidence limits). This figure along with other figures will be described in the following section.

Flexural Strength

Figure 93a shows the contribution of testing and production variation to the total variation measured in the flexural test. Figure 93a shows that the testing variation of 5.7% (28-30 psi) is significant for low levels of production variation. Figure 93b illustrates that at a production standard deviation of 6%, a value in the lower end of the range typically observed in the pavements investigated in this study, the variation associated with 95% confidence increased from 11% (testing variation, which is approximately 60 psi) to nearly 16% (testing variation + production variation, which is approximately 90 psi).

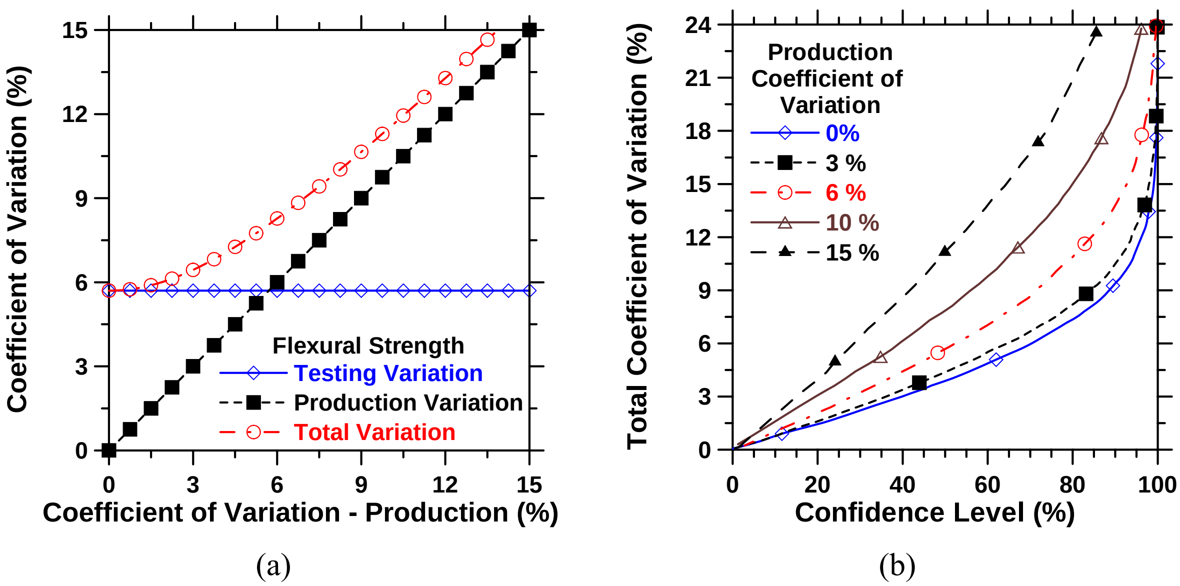


Figure 93. Flexural Strength: a) An Illustration of the Contribution of Testing and Production Variations to the Overall Total Standard Deviation (1s-limit) and b) the Influence of Production Variation on the Relationship Between Variation and Confidence Level.

At this time it should be noted that it would be recommended that the standard deviation and target mean strength should be considered simultaneously for the development of pay incentive charts. This is slightly different than the manner in which earlier specifications were developed in which a minimum satisfactory average strength was specified (Mindess et al. 2002). This shift to consider mean strength and standard deviation simultaneously is consistent with the recent FHWA Performance Related

Specification developments that illustrate how consistency in material properties can be related to improved long-term performance. To illustrate this concept Figure 94 can be used to show an example pay factor. Figure 94 was developed considering both the average flexural strength and standard deviation (Graveen et al. 2004). It should be noted that the lowest standard deviation (20 psi) was likely slightly low. It would be recommended for future developments that the minimum standard deviation associated with a bonus be in the range of 5.7% (i.e., 28 to 30 psi). It should also be noted that while Figure 94 shows the standard deviation appears in psi, it may be more appropriate to consider this variation as a coefficient of variation in accordance with Table 91.

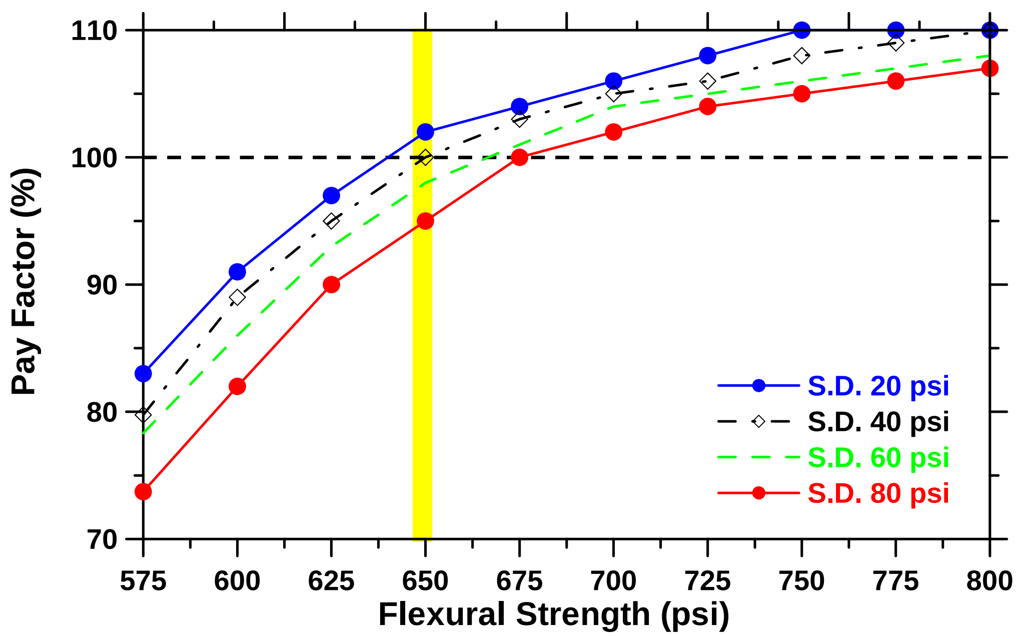


Figure 94. Example of a pay factor that includes both average strength and a measure of variation (Graveen et al. 2004).

While an approach is advocated that considers the standard deviation and target mean strength simultaneously, adaptation of the contents of this report to minimum strength specifications may require further description. Assume that an average strength of 570 psi is the minimum acceptable strength and the range of production variations described in Figure 95 are applied using a one-sided 95% confidence level Figure 95 can be developed. Figure 95 describes how 95% of the samples tested without production variation will have a strength of at least 516 psi and this value decreases to 509 psi for a production standard deviation of 17 psi (i.e., 3%), 491 psi for a production standard deviation of 34 psi (i.e., 6%), 461 psi for a production standard deviation of 57 psi (i.e., 10%), and 419 psi for a production standard deviation of 86 psi (i.e., 15%). This indicates that it would be very difficult to distinguish the production variation from the total variation until the variations reach a similar magnitude. Figure 95 illustrates the reality that even if the average strength is the same, the higher standard deviations would correspond to a wide range of strengths in the structure which can dramatically influence the long-term performance.

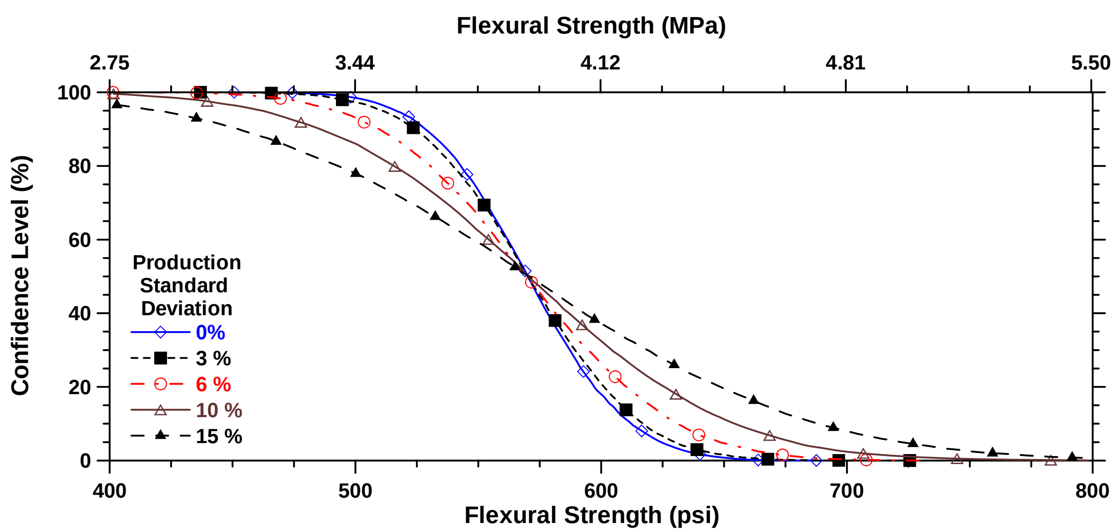


Figure 95. Flexural Strength versus confidence level for one-sided strength with an average strength of 570 psi.

It can also be observed that a total variation of 7% of the production variability composes approximately 60% of the total variability while a total variation of 8% corresponds to production variation to total variation ratio of 70%. These variations are similar to what was observed on the most consistent INDOT projects. As such it appears that a target total range of 40 to 45 psi may be appropriate for a target range for the standard deviation. A range of 30 to 40 psi may be an appropriate range for incentives.

Further work is recommended to relate these ranges to performance using life-cycle performance simulations.

Pavement Thickness

In addition to describing the flexural strength, thickness measurements of pavement cores were also described using a similar procedure. Figure 96a shows the contribution of testing and production variation to the total variation measured in determining the thickness of a core. Figure 96 shows that the testing variation (0.051 in) can be significant for low levels of production variation. Figure 96 illustrates that at a relatively low production standard deviation is comprised primarily of testing variation. It should be noted however that this testing variation is relatively low, and as such the minimum standard deviation that should be specified for thickness is 0.05 in.

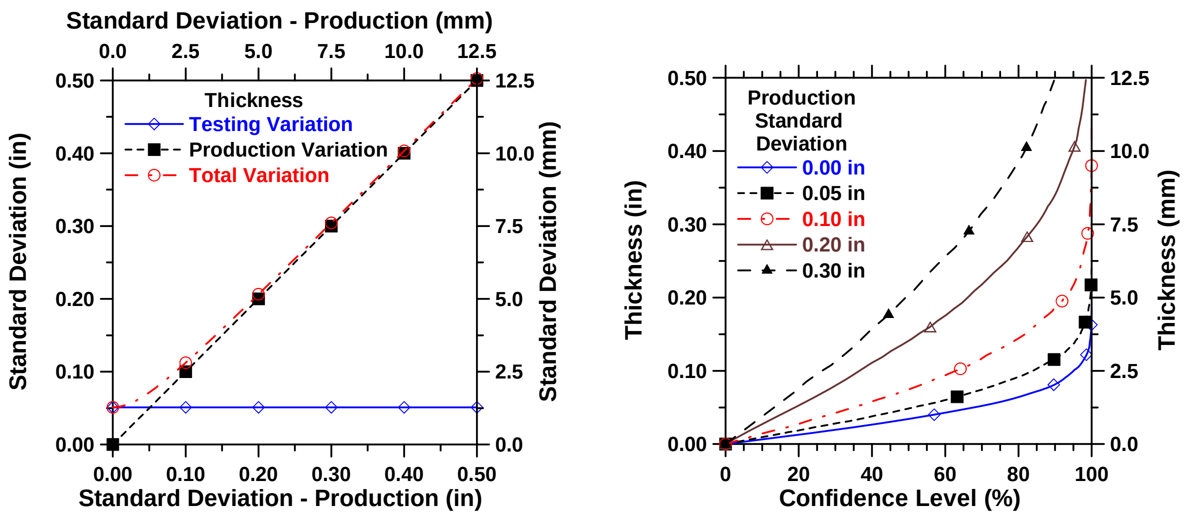


Figure 96. Thickness: a) An Illustration of the Contribution of Testing and Production Variations to the Overall Total Standard Deviation (1s-limit) and b) the Influence of Production Variation on the Relationship Between Variation and Confidence Level.

Air Content

In addition to describing the flexural strength, volumetric air content measurements were also described using a similar procedure. Figure 97a shows the contribution of testing and production variation to the total variation of air measured. Figure 97 shows that the testing variation (0.28% air by volume) can be the significant portion of total variability for low levels of production variation. It should be noted however that the testing variation that should be specified for an air content is 0.28% by volume. Field observations were found to range from 0.41 to 1.05%. It appears that a target total range of 0.28% to 0.50% air may be appropriate for an incentive range for the standard deviation of the air content, however further work is recommended to relate these ranges to performance using life-cycle performance simulations.

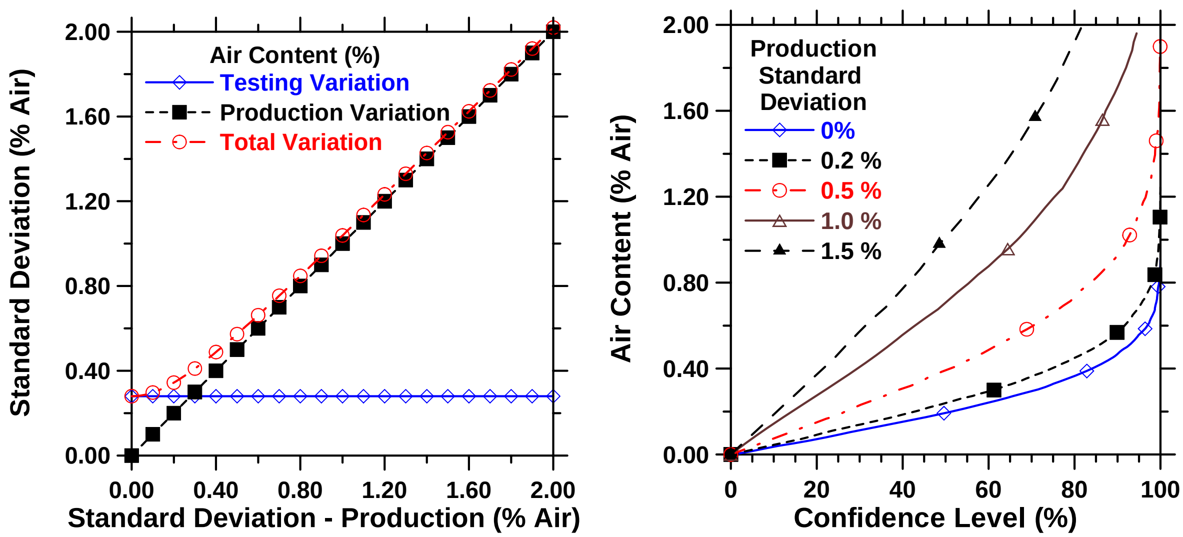


Figure 97. Air Content: a) An Illustration of the Contribution of Testing and Production Variations to the Overall Total Standard Deviation (1s-limit) and b) the Influence of Production Variation on the Relationship Between Variation and Confidence Level.

REFERENCES

American Association of State Highway and Transportation Officials, (1986). "AASHTO Guide for Design of Pavement Structures," Washington, D.C.

Aschenbrener, T., (1995). Demonstration of a Volumetric Acceptance Program. Proceedings of the Transportation Research Board, 74th Annual Meeting, Washington, D.C.

D'Angelo, J., Harman, T., Paugh, C., (2001). Evaluation of Volumetric Properties and Gyratory Compaction Slope for the Quality Control of Hot-Mix Asphalt Production. Preprint of the Paper Presented in Association of Asphalt Paving Technologist Annual Meeting and Technical Sessions, Clearwater Beach Florida. March 19-21.

Graveen, C., (2001). "The Use of Nondestructive Test Methods to Assess Pavement Quality in A Performance-Related Specification," Purdue University, M.S. Thesis, W. Lafayette, IN

Hand, A., Epps, A. (2000). Effects of Test Variability on Mixture Volumetrics and Mix Design Verification. Journal of the Association of Asphalt Paving Technologist, Vol. 69, pp. 635-674.

Hoerner, T.E. And Darter, M.I., (1999). Guide To Developing Performance-Related Specifications for PCC Pavements. Volume I: Practical Guide, Final Report and Appendix A. Report No. FHWA-RD-98-155. Washington, D.C., Federal Highway Administration.

Hoerner, T.E. And Darter, M.I., Tarr, S.M., Okamoto, P.A., (1999). Guide to Developing Performance-Related Specifications for PCC Pavements. Volume II: Appendix B – Field Demonstrations. Report No. FHWA-RD-98-156. Washington, D.C., Federal Highway Administration.

Hoerner, T. And Darter, M.I., Tarr, S.M., Okamoto, P.A., (1999). Guide to Developing Performance-Related Specifications for PCC Pavements. Volume III: Appendix C through F. Report No. FHWA-RD-98-171. Washington, D.C., Federal Highway Administration.

McCuen, R. (1985). Statistical Methods for Engineers. Prentice Hall, NJ.

Nantung, T., Smutzer R.K., Gallivan,V., (1999). Performance-Related Specifications for Concrete Pavements in Indiana, Document 1 - A proposal for PRS for Concrete Pavements in Indiana. Indiana Department of Transportation Research Division.

Schmitt, R., Hanna, A., Russell, J., Nordheim, E., (2001). Analysis of Bias in HMA Field Split-Sampling Testing. Preprint of the Paper Presented in Association of Asphalt

Paving Technologist Annual Meeting and Technical Sessions, Clearwater Beach Florida. March 19-21.

Weiss, W. J., Olek, J., Magee, B., Nantung, T. E., Smutzer, R. K., and Gallivan, V., (1999). Performance Related Specifications (PRS) For Concrete Pavements In Indiana, Project No. C-36-46R, File No. 5-11-18.

List of Appendices

Appendix

APPENDIX A

Coarse Aggregates

Source # 2421

Dolostone

U.S. Aggregates, Inc.

	Sieve Size, mm	#8
Percent Passing	63	100.0
	50	100.0
	37.5	100.0
	25	100.0
	19	94.3
	12.5	50.7
	9.5	20.8
	4.75	3.2
	2.36	2.3

Source # 2551

Dolostone

Hanson Aggregates

	Sieve Size, mm	#8
Percent Passing	63	100.0
	50	100.0
	37.5	100.0
	25	100.0
	19	90.9
	12.5	41.5
	9.5	21.8
	4.75	7.5
	2.36	4.2

APPENDIX A cont'd

Source # 2314

Limestone

Martin Marietta

	Sieve Size, mm	#8
Percent Passing	63	100.0
	50	100.0
	37.5	100.0
	25	100.0
	19	93.4
	12.5	41.1
	9.5	18.1
	4.75	4.0
	2.36	1.9

Source # 2451

Blast Furnace Slag

The Levy Company, Inc.

	Sieve Size, mm	#8
Percent Passing	63	100.0
	50	100.0
	37.5	100.0
	25	100.0
	19	88.7
	12.5	49.3
	9.5	32.9
	4.75	11.4
	2.36	6.6

APPENDIX A cont'd

Source # 2451

Steel Slag

The Levy Company, Inc.

	Sieve Size, mm	#11
Percent Passing	63	100.0
	50	100.0
	37.5	100.0
	25	100.0
	19	100.0
	12.5	100.0
	9.5	99.3
	4.75	67.4
	2.36	16.9
	0.6	4.6

APPENDIX B

Fine Aggregates

Source # 2183

Natural Sand

Vulcan Materials

	Sieve Size, mm	#23
Percent Passing	9.5	100.0
	4.75	100.0
	2.36	96.2
	1.18	67.0
	0.6	34.6
	0.3	10.0
	0.15	3.3
	0.075	1.6
	Pan	1.2

Source # 2312

Manufactured Sand

Hanson Aggregates

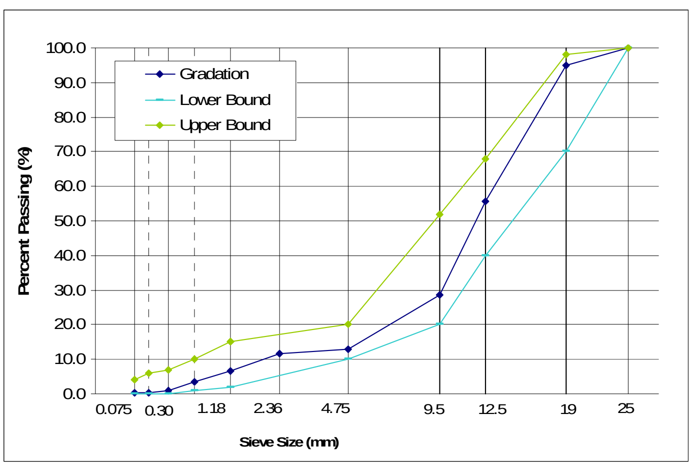
	Sieve Size, mm	#24
Percent Passing	9.5	100.0
	4.75	96.7
	2.36	85.9
	1.18	46.7
	0.6	22.7
	0.3	7.2
	0.15	1.6
	0.075	0.8
	Pan	0.4

Appendix C

Mix Information

Mix 1

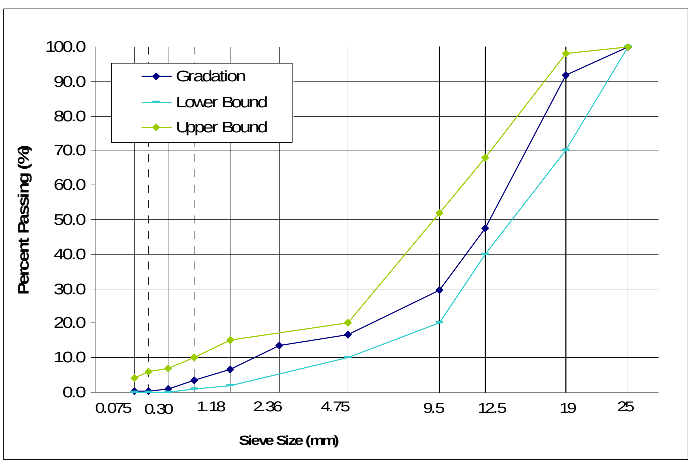
		2421	2183	Blend
		Percent Passing		
Sieve Size (mm)	Percent in Blend	90%	10%	-
	25.0	100.0	100.0	100.0
	19.0	94.3	100.0	94.9
	12.5	50.7	100.0	55.6
	9.5	20.8	100.0	28.7
	4.75	3.2	100.0	12.9
	2.36	2.3	96.2	11.7
	1.18	-	67.0	6.7
	0.60	-	34.6	3.5
	0.30	-	10.0	1.0
	0.15	-	3.3	0.3
	0.075	-	1.6	0.2



Appendix C cont'd

Mix 2

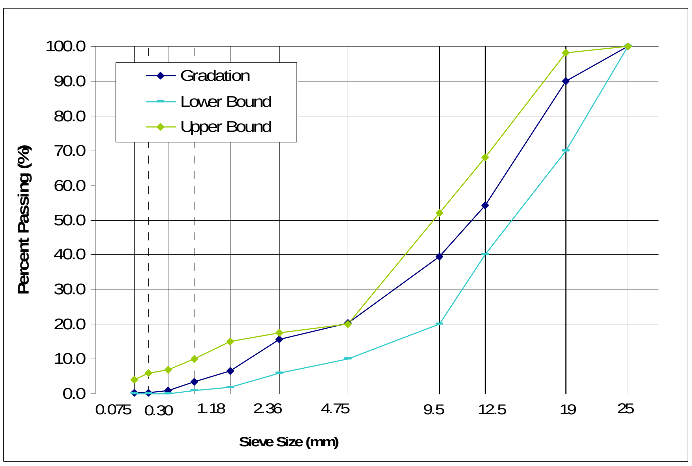
		2551	2183	Blend
		Percent Passing		
Sieve Size (mm)	Percent in Blend	90%	10%	-
	25.0	100.0	100.0	100.0
	19.0	90.9	100.0	91.8
	12.5	41.5	100.0	47.4
	9.5	21.8	100.0	29.6
	4.75	7.5	100.0	16.8
	2.36	4.2	96.2	13.4
	1.18	-	67.0	6.7
	0.60	-	34.6	3.5
	0.30	-	10.0	1.0
	0.15	-	3.3	0.3
	0.075	-	1.6	0.2



Appendix C cont'd

Mix 3

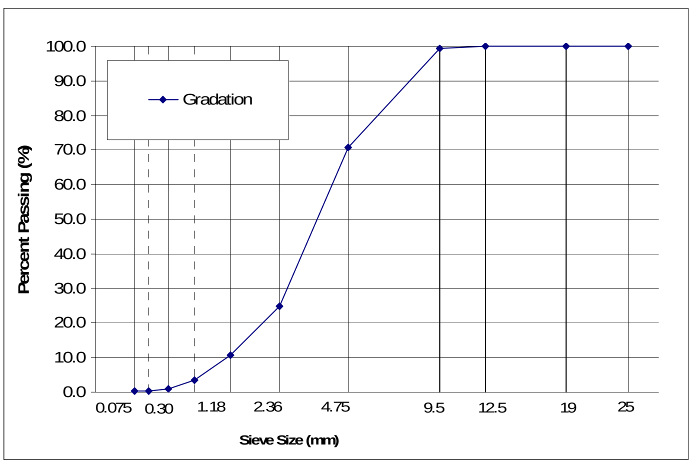
Sieve Size (mm)		2451	2183	Blend
		Percent Passing		
	Percent in Blend	90%	10%	-
	25.0	100.0	100.0	100.0
	19.0	88.7	100.0	89.8
	12.5	49.3	100.0	54.4
	9.5	32.9	100.0	39.6
	4.75	11.4	100.0	20.3
	2.36	6.6	96.2	15.6
	1.18	-	67.0	6.7
	0.60	-	34.6	3.5
	0.30	-	10.0	1.0
	0.15	-	3.3	0.3
	0.075	-	1.6	0.2



Appendix C cont'd

Mix 4

Sieve Size (mm)	2451	2183	Blend
	Percent Passing		
Percent in Blend	90%	10%	-
25.0	100.0	100.0	100.0
19.0	100.0	100.0	100.0
12.5	100.0	100.0	100.0
9.5	99.3	100.0	99.4
4.75	67.4	100.0	70.7
2.36	16.9	96.2	24.8
1.18	4.6	67.0	10.8
0.60	-	34.6	3.5
0.30	-	10.0	1.0
0.15	-	3.3	0.3
0.075	-	1.6	0.2



Appendix D

Date of Testing	Test Series	Test	Specimen id	Rep	Mass Oven Dry, A (g)	Empty container with water, B (g)	Specimen in water, C (g)	SSD Mass, S (g)	Container Calibration Weight (N1,N2,N3) (g)	Container Calibration Weight (Avg) (g)	Dry Sample Weight (N1,N2,N3) (g)	Dry Sample Weight (Avg) (g)	Sample Weight in Container Filled with Water (N1,N2,N3) (g)	Sample Weight in Container Filled with Water (Avg) (g)	Bag Weight (g)	Rubber Sheets Combined Wt. (g)	Dry Sample Weight (g)	Weight of Sealed Sample Opened in Water (g)	Percent Absorption (%)	Apparent Density	Bulk Specific Gravity, (SSD)	Bulk Specific Gravity, (BSG)
07/13/2004	1	T 84	2183 (Nat)	1	487.3	681.3	989.4	495.1											1.601	2.719	2.648	2.606
07/13/2004	1	T 84	2183 (Nat)	2	491.1	681.2	991.6	499.7											1.751	2.718	2.640	2.594
07/19/2004	2	T 84	2183 (Nat)	1	493.0	681.4	993.2	499.9											1.400	2.721	2.658	2.621
07/19/2004	2	T 84	2183 (Nat)	2	492.9	681.5	993.1	500.6											1.562	2.719	2.649	2.608
07/22/2004	3	T 84	2183 (Nat)	1	492.3	681.1	992.4	500.1											1.584	2.720	2.649	2.608
07/22/2004	3	T 84	2183 (Nat)	2	491.8	681.1	992.3	500.5											1.769	2.723	2.644	2.598
07/12/2004	1	Corelok	2183 (Nat)	1					4086.000	4086.000	500.200	500.200	4400.500	4400.500	28.400	0.000	1000.600	631.000	0.974	2.730	2.685	2.659
07/12/2004	1	Corelok	2183 (Nat)	2					4086.000	4086.000	500.500	500.500	4399.900	4399.900	28.500	0.000	1000.500	630.600	1.779	2.727	2.647	2.601
07/15/2004	2	Corelok	2183 (Nat)	1					4086.000	4086.000	500.200	500.200	4399.500	4399.500	28.400	0.000	1000.100	630.500	1.890	2.728	2.644	2.595
07/15/2004	2	Corelok	2183 (Nat)	2					4086.000	4086.000	500.300	500.300	4399.600	4399.600	28.400	0.000	1000.700	630.900	1.880	2.729	2.644	2.595
07/21/2004	3	Corelok	2183 (Nat)	1					4086.000	4086.000	500.200	500.200	4399.400	4399.400	28.600	0.000	1000.700	630.300	1.820	2.724	2.643	2.596
07/21/2004	3	Corelok	2183 (Nat)	2					4086.000	4086.000	500.400	500.400	4400.000	4400.000	28.800	0.000	1000.000	630.500	1.764	2.729	2.65	2.604
07/13/2004	1	T 84	2312 (Man)	1	485.7	681.5	989.4	495.6											2.038	2.732	2.640	2.588
07/13/2004	1	T 84	2312 (Man)	2	490.3	681.3	991.7	500											1.978	2.725	2.637	2.586
07/19/2004	2	T 84	2312 (Man)	1	491.7	681.3	993.5	499.9											1.668	2.739	2.663	2.620
07/19/2004	2	T 84	2312 (Man)	2	491	681.3	992.3	499.5											1.731	2.728	2.650	2.605
07/22/2004	3	T 84	2312 (Man)	1	490.6	681.1	992.4	500											1.916	2.736	2.650	2.600
07/22/2004	3	T 84	2312 (Man)	2	492.1	681.1	993.6	500.7											1.748	2.740	2.660	2.615
07/12/2004	1	Corelok	2312 (Man)	1					4086.000	4086.000	500.300	500.300	4401.300	4401.300	28.600	0.000	1000.000	632.800	1.676	2.746	2.669	2.625
07/12/2004	1	Corelok	2312 (Man)	2					4086.000	4086.000	500.500	500.500	4401.900	4401.900	28.500	0.000	1000.100	633.400	1.592	2.750	2.677	2.635
07/15/2004	2	Corelok	2312 (Man)	1					4086.000	4086.000	500.600	500.600	4402.500	4402.500	28.300	0.000	1000.100	633.400	0.818	2.750	2.712	2.690
07/15/2004	2	Corelok	2312 (Man)	2					4086.000	4086.000	500.500	500.500	4402.200	4402.200	28.500	0.000	1000.900	633.900	0.914	2.750	2.707	2.683
07/21/2004	3	Corelok	2312 (Man)	1					4086.000	4086.000	500.600	500.600	4401.700	4401.700	28.600	0.000	1000.000	632.500	0.976	2.744	2.699	2.672
07/21/2004	3	Corelok	2312 (Man)	2					4086.000	4086.000	500.700	500.700	4402.100	4402.100	28.600	0.000	1000.900	633.500	0.927	2.747	2.704	2.679

Appendix E

Date of Testing	Test Series	Test	Specimen id	Replicate	Mass Oven Dry, A (g)	Mass SSD in air, B (g)	Mass in Water, C (g)	Test Temp. (deg C)	Container Calibration Weight (Na,N2,N3) (g)	Container Calibration Weight (avg) (g)	Dry Sample Weight (Na,N2,N3) (g)	Dry Sample Weight (avg) (g)	Sample Weight in Container Filled with Water (Na,N2,N3) (g)	Sample Weight in Container Filled with Water (avg) (g)	Bag Weight (g)	Rubber Sheets Combined Wt. (g)	Dry Sample Weight (g)	Weight of Sealed Sample Opened in Water (g)	Percent absorption (%)	apparent Specific Gravity (Gsa)	Bulk Specific Gravity, (SSD)	Bulk Specific Gravity, (BSG)
05/12/2004	1	T 85	2421	1	5375.5	5432.0	3453.3	24.0											1.051	2.797	2.745	2.717
05/12/2004	1	T 85	2421	2	5520.7	5579.3	3544.0	23.0											1.061	2.793	2.741	2.712
05/14/2004	2	T 85	2421	1	5349.8	5408.9	3443.3	23.0											1.105	2.806	2.752	2.722
05/14/2004	2	T 85	2421	2	5540.0	5599.7	3563.0	22.0											1.078	2.802	2.749	2.720
06/16/2004	3	T 85	2421	1	5348.3	5420.7	3443.5	23.0											1.354	2.808	2.742	2.705
06/16/2004	3	T 85	2421	2	5537.5	5609.9	3561.0	23.0											1.307	2.802	2.738	2.703
05/13/2004	1	Corelok	2421	1				25.0	5597.800	5597.800	1000.600	1000.600	6239.900	6239.900	69.100	201.200	1999.800	1316.800	0.397	2.822	2.802	2.791
05/13/2004	1	Corelok	2421	2				25.0	5597.800	5597.800	1000.300	1000.300	6231.900	6231.900	69.300	201.000	2000.200	1280.600	0.200	2.684	2.675	2.670
06/15/2004	2	Corelok	2421	1				25.0	5597.800	5597.800	1000.400	1000.400	6238.000	6238.000	69.300	200.900	2000.100	1316.300	0.543	2.820	2.792	2.777
06/15/2004	2	Corelok	2421	2				25.0	5597.800	5597.800	1000.100	1000.100	6238.600	6238.600	69.300	201.000	2000.500	1317.700	0.520	2.824	2.798	2.783
06/17/2004	3	Corelok	2421	1				25.0	5597.800	5597.800	1000.300	1000.300	6238.300	6238.300	68.800	200.800	1999.800	1314.900	0.445	2.815	2.793	2.780
06/17/2004	3	Corelok	2421	2				25.0	5597.800	5597.800	1000.700	1000.700	6239.000	6239.000	68.900	200.900	2000.100	1315.200	0.406	2.815	2.795	2.784
05/12/2004	1	T 85	2551	1	5329.7	5521.2	3336.8	23.0											3.593	2.674	2.528	2.440
05/12/2004	1	T 85	2551	2	5448.0	5645.8	3412.0	23.0											3.631	2.676	2.527	2.439
05/15/2004	2	T 85	2551	1	5326.4	5559.7	3378.2	24.0											4.380	2.734	2.549	2.442
05/15/2004	2	T 85	2551	2	5444.3	5686.8	3453.3	23.0											4.454	2.734	2.546	2.438
06/16/2004	3	T 85	2551	1	5323.8	5569.5	3375.7	23.0											4.615	2.733	2.539	2.427
06/16/2004	3	T 85	2551	2	5441.9	5693.0	3432.1	23.0											4.614	2.708	2.518	2.407
05/14/2004	1	Corelok	2551	1				25.0	5597.800	5597.800	1000.800	1000.800	6180.800	6180.800	69.100	201.000	2000.500	1320.300	6.470	2.835	2.55	2.395
05/14/2004	1	Corelok	2551	2				25.0	5597.800	5597.800	1000.400	1000.400	6211.200	6211.200	69.300	201.000	1999.900	1320.400	3.433	2.837	2.674	2.585
06/15/2004	2	Corelok	2551	1				25.0	5597.800	5597.800	1000.700	1000.700	6217.200	6217.200	69.200	201.000	2000.100	1320.000	2.825	2.835	2.699	2.624
06/15/2004	2	Corelok	2551	2				25.0	5597.800	5597.800	1000.300	1000.300	6218.100	6218.100	69.000	201.000	2000.200	1321.700	2.791	2.841	2.706	2.632
06/25/2004	3	Corelok	2551	1				25.0	5597.800	5597.800	1000.200	1000.200	6216.500	6216.500	72.200	200.400	2000.100	1320.100	2.890	2.837	2.698	2.622
06/25/2004	3	Corelok	2551	2				25.0	5597.800	5597.800	1000.300	1000.300	6216.800	6216.800	72.400	200.600	2000.600	1320.900	2.889	2.839	2.699	2.623
06/15/2004	1	T 85	2451 - BF	1	5706.5	5971.5	3453.7	23.0											4.644	2.533	2.372	2.266
06/15/2004	1	T 85	2451 - BF	2	5338.8	5620.0	3248.9	22.0											5.267	2.555	2.370	2.252
06/18/2004	2	T 85	2451 - BF	1	5701.6	6087.4	3548.2	22.0											6.767	2.648	2.397	2.245
06/18/2004	2	T 85	2451 - BF	2	5336.2	5675.5	3330.5	22.0											6.358	2.661	2.420	2.276
06/30/2004	3	T 85	2451 - BF	1	5707.7	6043.0	3544.6	23.0											5.875	2.639	2.419	2.285
06/30/2004	3	T 85	2451 - BF	2	5322.9	5645.3	3323.4	23.0											6.057	2.662	2.431	2.292
06/17/2004	1	Corelok	2451 - BF	1				25.0	5597.800	5597.800	1000.400	1000.400	6193.600	6193.600	69.200	200.800	1999.400	1381.100	8.245	3.106	2.676	2.473
06/17/2004	1	Corelok	2451 - BF	2				25.0	5597.800	5597.800	1000.200	1000.200	6194.300	6194.300	69.200	200.900	2000.800	1324.300	5.276	2.850	2.608	2.478
06/29/2004	2	Corelok	2451 - BF	1				25.0	5597.800	5597.800	1000.400	1000.400	6193.800	6193.800	72.000	200.500	2000.900	1317.800	5.029	2.825	2.598	2.474
06/29/2004	2	Corelok	2451 - BF	2				25.0	5597.800	5597.800	1000.100	1000.100	6200.300	6200.300	72.400	200.600	2000.000	1320.800	4.541	2.840	2.63	2.515
07/01/2004	3	Corelok	2451 - BF	1				25.0	5597.800	5597.800	1000.300	1000.300	6194.700	6194.700	72.100	200.500	2000.000	1318.900	5.017	2.832	2.604	2.480
07/01/2004	3	Corelok	2451 - BF	2				25.0	5597.800	5597.800	1000.500	1000.500	6198.900	6198.900	72.500	200.600	2000.100	1320.200	4.672	2.837	2.622	2.505

Appendix E Cont'd

Date of Testing	Test Series	Test	Specimen id	Replicate	Mass Oven Dry, A (g)	Mass SSD in air, B (g)	Mass in Water, C (g)	Test Temp. (deg C)	Container Calibration Weight (Na,N2,N3) (g)	Container Calibration Weight (avg) (g)	Dry Sample Weight (Na,N2,N3) (g)	Dry Sample Weight (avg) (g)	Sample Weight in Container Filled with Water (Na,N2,N3) (g)	Sample Weight in Container Filled with Water (avg) (g)	Bag Weight (g)	Rubber Sheets Combined Wt. (g)	Dry Sample Weight (g)	Weight of Sealed Sample Opened in Water (g)	Percent absorptio n (%)	apparent Specific Gravity (Gsa)	Bulk Specific Gravity, (SSD)	Bulk Specific Gravity, (BSG)
06/15/2004	1	T 85	2451 - SS	1	5893.8	5987.0	4228.9	23.0											1.581	3.540	3.405	3.352
06/15/2004	1	T 85	2451 - SS	2	5744.4	5853.1	4119.6	23.0											1.892	3.535	3.376	3.314
06/17/2004	2	T 85	2451 - SS	1	5895.2	6019.6	4240.3	24.0											2.110	3.562	3.383	3.313
06/17/2004	2	T 85	2451 - SS	2	5746.7	5855.7	4129.9	24.0											1.897	3.554	3.393	3.330
06/24/2004	3	T 85	2451 - SS	1	5902.5	5997.3	4237.8	23.0											1.606	3.546	3.409	3.355
06/24/2004	3	T 85	2451 - SS	2	5747.8	5854.2	4127.8	23.0											1.851	3.548	3.391	3.329
06/16/2004	1	Corelok	2451 - SS	1				25.0	5597.800	5597.800	1000.100	1000.100	6311.900	6311.900	69.200	200.900	2000.000	1471.000	0.873	3.607	3.527	3.497
06/16/2004	1	Corelok	2451 - SS	2				25.0	5597.800	5597.800	1000.000	1000.000	6311.800	6311.800	69.100	200.900	2000.000	1469.100	0.780	3.595	3.524	3.497
06/23/2004	2	Corelok	2451 - SS	1				25.0	5597.800	5597.800	1000.300	1000.300	6311.500	6311.500	72.100	200.600	2000.500	1468.800	0.817	3.593	3.519	3.490
06/23/2004	2	Corelok	2451 - SS	2				25.0	5597.800	5597.800	1000.200	1000.200	6311.500	6311.500	72.400	200.600	2000.800	1470.700	0.896	3.604	3.522	3.491
07/01/2004	3	Corelok	2451 - SS	1				25.0	5597.800	5597.800	1000.400	1000.400	6311.100	6311.100	72.100	200.500	2000.100	1468.200	0.849	3.591	3.514	3.485
07/01/2004	3	Corelok	2451 - SS	2				25.0	5597.800	5597.800	1000.100	1000.100	6311.500	6311.500	71.900	200.500	2000.500	1467.400	0.732	3.584	3.518	3.492
06/14/2004	1	T 85	2314	1	5859.2	5941.2	3690.3	22.0											1.400	2.701	2.639	2.603
06/14/2004	1	T 85	2314	2	6072.3	6163.2	3822.7	22.0											1.497	2.699	2.633	2.594
06/17/2004	2	T 85	2314	1	5856.3	5950.8	3691.5	22.0											1.614	2.705	2.634	2.592
06/17/2004	2	T 85	2314	2	6069.4	6175.1	3824.9	24.0											1.742	2.704	2.627	2.583
06/25/2004	3	T 85	2314	1	6013.7	6107.6	3791.2	22.0											1.561	2.706	2.637	2.596
06/25/2004	3	T 85	2314	2	5906.4	6000.3	3721.4	22.0											1.590	2.703	2.633	2.592
06/16/2004	1	Corelok	2314	1				25.0	5597.800	5597.800	1000.600	1000.600	6225.600	6225.600	69.200	200.800	2000.000	1287.700	0.369	2.711	2.694	2.684
06/16/2004	1	Corelok	2314	2				25.0	5597.800	5597.800	1000.300	1000.300	6224.700	6224.700	69.200	200.800	2000.000	1288.700	0.490	2.715	2.692	2.679
06/24/2004	2	Corelok	2314	1				25.0	5597.800	5597.800	1000.200	1000.200	6224.400	6224.400	72.000	200.600	2000.800	1288.200	0.480	2.712	2.69	2.677
06/24/2004	2	Corelok	2314	2				25.0	5597.800	5597.800	1000.600	1000.600	6224.700	6224.700	71.700	200.700	2000.500	1288.300	0.487	2.713	2.691	2.678
06/29/2004	3	Corelok	2314	1				25.0	5597.800	5597.800	1000.400	1000.400	6223.700	6223.700	72.300	200.400	2000.000	1285.800	0.471	2.705	2.684	2.671
06/29/2004	3	Corelok	2314	2				25.0	5597.800	5597.800	1000.400	1000.400	6224.700	6224.700	72.000	200.600	2000.700	1285.800	0.346	2.704	2.688	2.678

Appendix F

Date of Testing	Test Series	Test	Specimen id	Replicate	Mass Oven Dry, A (g)	Mass Container w/ water (D)	Mass of Sample and container (E)	Supplemental (A)	Test Temp. (deg C)	Bag Weight (g)	Rubber Sheets Combined Weight (g)	Sample Weight in air (g)	Weight of Sample Opened in Water (g)	Density of Water (g/cm3) for temperature correction	Gmm A/(A+D-E)	Gmm A/(A+D-E) w/ suppl. (A)
11/19/2004	1	T 209	Mix 1	1	3344.3	7388.6	9475.7	3372.9	26						2.660	2.623
01/24/2005	1	T 209	Mix 1	2	3474.1	7388.2	9551.7	3477.6	24						2.651	2.646
12/29/2004	2	T 209	Mix 1	1	3345.0	7388.4	9474.4	3349.4	25						2.657	2.651
12/29/2004	2	T 209	Mix 1	2	3475.1	7387.5	9552.8	3479.6	25						2.653	2.647
01/06/2005	3	T 209	Mix 1	1	3344.9	7390.1	9481.1	3348.6	25						2.668	2.663
01/06/2005	3	T 209	Mix 1	2	3475.4	7392.1	9555.6	3479.6	25						2.649	2.644
12/27/2004	1	Corelok	Mix 1	1					25	68.2	0	2000.2	1244.9	1	2.674	
12/27/2004	1	Corelok	Mix 1	2					25	68.2	0	2000	1238.8	1	2.653	
01/03/2005	2	Corelok	Mix 1	1					25	68.1	0	2000.5	1244.3	1	2.671	
01/03/2005	2	Corelok	Mix 1	2					25	68.2	0	2000.5	1238.5	1	2.651	
01/04/2005	3	Corelok	Mix 1	1					25	68.8	0	2000	1242.3	1	2.666	
01/04/2005	3	Corelok	Mix 1	2					25	68.8	0	2000.5	1240.3	1	2.657	
01/04/2005	1	T 209	Mix 2	1	2483.9	7388.0	8870.3	2490.0	25						2.480	2.471
01/04/2005	1	T 209	Mix 2	2	2505.3	7387.8	8891.3	2515.1	25						2.501	2.486
01/06/2005	2	T 209	Mix 2	1	2485.1	7390.3	8873.8	2490.6	25						2.481	2.473
01/06/2005	2	T 209	Mix 2	2	2503.2	7390.1	8892.9	2513.7	25						2.502	2.487
01/12/2005	3	T 209	Mix 2	1	2476.7	7391.9	8869.8	2488.8	25						2.480	2.462
01/12/2005	3	T 209	Mix 2	2	2504.3	7389.9	8892.1	2513.1	26						2.499	2.486
01/13/2005	1	Corelok	Mix 2	1					25	68.9	0	2000.9	1186.3	1	2.479	
12/28/2004	1	Corelok	Mix 2	2					25	68.3	0	2000	1209.9	1	2.555	
01/03/2005	2	Corelok	Mix 2	1					25	68.5	0	2000.1	1199.5	1	2.521	
01/03/2005	2	Corelok	Mix 2	2					25	68.8	0	2000.7	1203.6	1	2.533	
01/05/2005	3	Corelok	Mix 2	1					25	68.6	0	2000.3	1185.9	1	2.479	
01/05/2005	3	Corelok	Mix 2	2					25	68.7	0	2000.7	1194.7	1	2.505	
01/05/2005	1	T 209	Mix 3	1	2525.5	7390.4	8914.4	2573.3	25						2.522	2.452
01/05/2005	1	T 209	Mix 3	2	2498.8	7391.5	8899.3	2548.1	25						2.521	2.449
01/09/2005	2	T 209	Mix 3	1	2527.9	7392.1	8917.5	2571.9	24						2.522	2.458
01/09/2005	2	T 209	Mix 3	2	2505.1	7390.9	8907.3	2556.2	25						2.534	2.458
01/12/2005	3	T 209	Mix 3	1	2535.8	7389.7	8922.8	2579.7	25						2.529	2.465
01/12/2005	3	T 209	Mix 3	2	2513.7	7389.9	8907.3	2558.8	25						2.523	2.457
01/03/2005	1	Corelok	Mix 3	1					25	68.5	0	2000.2	1210.1	1	2.555	
01/03/2005	1	Corelok	Mix 3	2					25	68.4	0	2000.1	1208.6	1	2.551	
01/06/2005	2	Corelok	Mix 3	1					25	68.5	0	2000.2	1205	1	2.539	
01/06/2005	2	Corelok	Mix 3	2					25	68.5	0	2000.8	1206.9	1	2.544	
01/10/2005	3	Corelok	Mix 3	1					24	68.5	0	2000.1	1205.1	1	2.539	
01/10/2005	3	Corelok	Mix 3	2					25	68.5	0	2000.6	1203	1	2.532	
01/19/2005	1	T 209	Mix 4	1	2491.0	7388.6	9070.2	2491.3	25						3.078	3.077
12/29/2004	1	T 209	Mix 4	2	2472.5	7387.2	9053.3	2474.1	25						3.066	3.062
01/04/2005	2	T 209	Mix 4	1	2491.5	7388.3	9067.7	2492.2	25						3.068	3.066
01/04/2005	2	T 209	Mix 4	2	2472.9	7388.2	9055.8	2473.8	25						3.071	3.068
01/13/2005	3	T 209	Mix 4	1	2491.4	7390.9	9072.4	2492.4	25						3.076	3.074
01/13/2005	3	T 209	Mix 4	2	2472.9	7390.6	9057.5	2473.9	25						3.068	3.066
12/28/2004	1	Corelok	Mix 4	1					25	68.3	0	2000.6	1345.4	1	3.088	
12/28/2004	1	Corelok	Mix 4	2					25	68	0	1999.6	1345.3	1	3.091	
01/03/2005	2	Corelok	Mix 4	1					24	69.1	0	2000.6	1345.4	1	3.088	
01/03/2005	2	Corelok	Mix 4	2					25	68.7	0	2000.4	1345.9	1	3.091	
01/05/2005	3	Corelok	Mix 4	1					25	68.5	0	2000.3	1342.7	1	3.076	
01/05/2005	3	Corelok	Mix 4	2					25	68.3	0	2000	1345.6	1	3.091	

Appendix G

Parameter	Test Metho	Data Source	Testing Agency	Variability								Single Operator Limit
				s_T		s_T^*		s_S+s_{TE}		s_{TE}		
				Avg.	St. Dv	Avg.	St. Dv	Avg.	St. Dv	Avg.	St. Dv	(1s)
Gmm	AASHTO T209	I	S	2.492	0.0154	2.482	0.0126			2.485	0.0079	0.004
		I	C - T	2.475	0.0119							0.004
		I	C - R	2.475	0.0123							0.004
		III	S	2.49	0.0172*							0.0064[a]
		IV	PU	2.686	0.007			2.686	0.009	2.686	0.004	0.004
	AASHTO T209 Supp.	IV	PU	2.662	0.009			2.662	0.009	2.662	0.008	0.0064
	Corelok	IV	PU	2.701	0.014			2.701	0.014	2.701	0.011	0.004
Pb	ITM 586	I	S	5.31	0.23	5.27	0.2					0.04
		I	C - T	5.24	0.22							0.04
		I	C - R	5.29	0.26							0.04
		II	S	5.06	0.062							0.04
		II	C - T	5.05	0.093							0.04
Pill Gmb	AASHTO T166	I	S	2.403	0.0175	2.391	0.0092	2.403	0.0086	2.395	0.0044	0.008
		I	C - T	2.375	0.0154			2.375	0.0078			0.008
		I	C - R	2.379	0.0171			2.379	0.0066			0.008
Pill Va	AASHTO PP28	I	S	3.6	0.93	3.62	0.6	3.6	0.31	3.62	0.36	0.32
		I	C - T	4.02	0.73			4.03	0.32			0.32
		I	C - R	3.86	0.82			3.86	0.27			0.32
Pill VMA	AASHTO PP28	I	S	14.06	0.6194	14.01	0.376	14.06	0.3108			0.25[b]
		I	C - T	14.52	0.5646			14.54	0.2834			0.25[b]
		I	C - R	14.18	0.6068			14.18	0.2417			0.25[b]
Core Gmb	AASHTO T166	I	S	2.299	0.0263	2.294	0.0147	2.297	0.0283	2.292	0.0042	0.008
		I	C - R	2.363	0.0285			2.363	0.027			0.008
Core Density	AASHTO T166	I	S	92.35	1.17	92.4	0.72	92.25	1.12[a]	92.17	0.35	0.52
		I	C - R	92.48	1.12			92.48	1.04[a]			0.52
Core Gmb	AASHTO T275	I	S	2.281	0.0271	2.291	0.0226	2.281	0.0249	2.286	0.0022	0.028
		I	C - R	2.305	0.032			2.305	0.0312			0.028
Core Density	AASHTO T275	I	S	91.08	1.1	90.93	0.9	91.08	1.16[a]	91.31	0.42	1.14
		I	C - R	93.6	1.119			93.6	1.40[a]			1.14
G_{sb}	AASHTO T85	III	S	2.617	0.009							0.009
		IV	PU					2.668	0.010	2.668	0.013	0.009
	Corelok	IV	PU					2.800	0.031	2.800	0.033	0.009
SSD G_{sb}	AASHTO T85	III	S	2.646	0.010							0.007
		IV	PU					2.741	0.008	2.741	0.012	0.007
	Corelok	IV	PU					2.856	0.028	2.856	0.030	0.007
G_{sa}	AASHTO T85	III	S	2.706	0.013							0.007
		IV	PU					2.876	0.007	2.876	0.023	0.007
	Corelok	IV	PU					2.964	0.035	2.964	0.037	0.007
Water abs.	AASHTO T85	III	S	1.51	0.046							0.088
		IV	PU					2.92	0.124	2.92	0.373	0.088
	Corelok	IV	PU					2.14	0.540	2.14	0.620	0.088
G_{sb}	AASHTO T84	III	S	2.572	0.038							0.011
		IV	PU					2.604	0.008	2.604	0.012	0.011
	Corelok	IV	PU					2.636	0.015	2.636	0.028	0.011
SSD G_{sb}	AASHTO T84	III	S	2.614	0.030							0.0095
		IV	PU					2.649	0.006	2.649	0.008	0.0095
	Corelok	IV	PU					2.673	0.010	2.673	0.018	0.0095
G_{sa}	AASHTO T84	III	S	2.684	0.026							0.0095
		IV	PU					2.727	0.004	2.727	0.004	0.0095
	Corelok	IV	PU					2.738	0.002	2.738	0.002	0.0095
Water abs.	AASHTO T84	III	S	1.59	0.41							0.11
		IV	PU					1.73	0.098	1.73	0.139	0.11
	Corelok	IV	PU					1.42	0.193	1.42	0.393	0.11
	a) multi-operator variation, b) Adjusted Limit											

Appendix H

Test Metho	Parameter	Data Source	Testing Agency	Total Variability (S_T)						Sampling + Testing Variability ($S_S + S_{TE}$)						Operator Limit	Operator Limit
				Single Operator			Multi-Operator			Single Operator			Multi-Operator				
				Avg.	St. Dv	CV (%)	Avg.	St. Dv	CV (%)	Avg.	St. Dv	CV (%)	Avg.	St. Dv	CV (%)	(1s)	(1s)
AASHTO T	Plastic Air C	I	S										6.1	0.14	2.6		0.28
		II	C				6.5	0.41	6.3								0.28
		III	C/S										6.5	0.14	2.2		0.28
		VIII	S				6.8	1.012	11.93								
AASHTO T	Plastic Unit	II	C	143.4	1.22	0.9										0.65	0.82
		III	C/S										144.3	0.46	0.3	0.65	0.82
AASHTO T	Flexural Str	II	C	702	46.5	6.6				702	20.6[a]	2.9				5.7%[a]	7.0%[a]
		III	C/S							686	20.2	2.9				7.0%[a,c]	7.0%[a]
		IV	S	682	43	6.2										7.0%[a,c]	7.0%[a]
		V	S							672	38.0	5.3				4.7%[a,c]	7.0%[a]
ASTM C39	Compressiv	V	S							4103	151	3.7				2.37%[a,b]	
		VII	S							5238	214	3.2	5238	267	4.8	2.37%[a,b]	
		VIII	S				6263	555	8.5	6190	202	2.3				2.37%[a,b]	
ASTM 496	Split Tensil	V	S							524	25	4.8				5.0%[a]	
ITM 404	Pavement T	IV	S	14.4	0.31	2.1										-	-
		X	S				12.45	0.051	0.41	12.45	0.047	0.33				-	-
AASHTO T	Coarse Agg	VI	S	2.684	0.02	0.8										0.007	0.011
		IX	S	2.682	0.02	0.7							2.67	0.01	0.4	0.007	0.011
	Coarse Agg	VI	S	1.963	0.48	24.6										0.088	0.145
		IX	S	1.975	0.45	20.7							1.386	0.19	13.7	0.088	0.145
	Coarse Agg	IX	S										2.634	0.014	0.5	0.009	0.013
AASHTO T	Fine Aggre	VI	S	2.638	0.02	0.8										0.0095	0.020
		IX	S	2.637	0.02	0.6							2.628	0.041	1.6	0.0095	0.020
	Fine Aggre	VI	S	1.65	0.27	16.3										0.11	0.23
		IX	S	1.648	0.09	12.4							1.644	0.315	19.2	0.11	0.23
	Fine Aggre	IX	S										2.585	0.043	1.7	0.011	0.145
	a) Coefficient of Variation, b) Laboratory Conditions, c) Adjusted 1s Limit																